Parachute Seminar

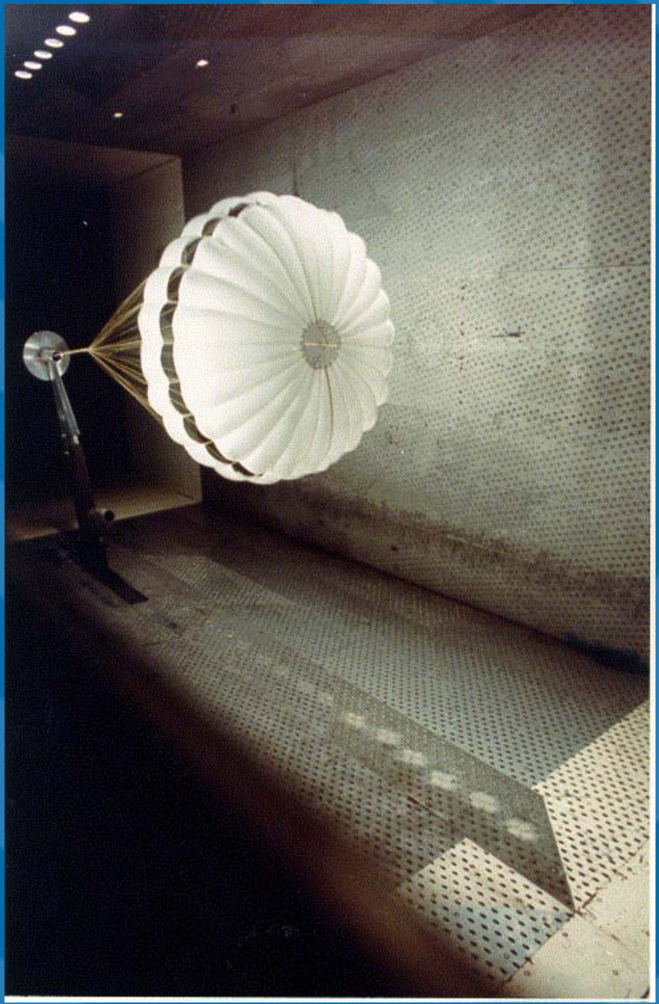
3rd International Planetary Probe Workshop

SUPERSONIC PARACHUTES

Steve Lingard
Vorticity Ltd
steve.lingard@vorticity-systems.com

Supersonic parachute needs

- weapons systems
- REV recovery
- space vehicle recovery
- space vehicle descent systems
  - Access to high altitude landing sites on Mars
  - Delivery of large payloads to Mars
    - Mach 3 performance needed



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Requirements

- high drag to weight ratio
- predictable drag and inflation performance
- act to stabilise not destabilise the parachute-payload system
- withstand high dynamic pressure loading or for some planetary entry scenarios function at low dynamic pressure
- high aeroelastic loading (ribbon flutter and pulsation)
- aerokinetic heating
- also perform at subsonic speeds

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Supersonic parachute behavior

- Current knowledge
  - Understanding poor
  - Few data exist
  - Testing has been ad hoc
  - Data fail to separate specific effects
  - Data incomplete
- Parachute behavior adversely affected by supersonic flow
  - Drag loss at low supersonic speeds
  - Drag loss for some types (DGB) in transonic regime
  - Reduction of flying diameter
  - Pulsation of canopy mouth

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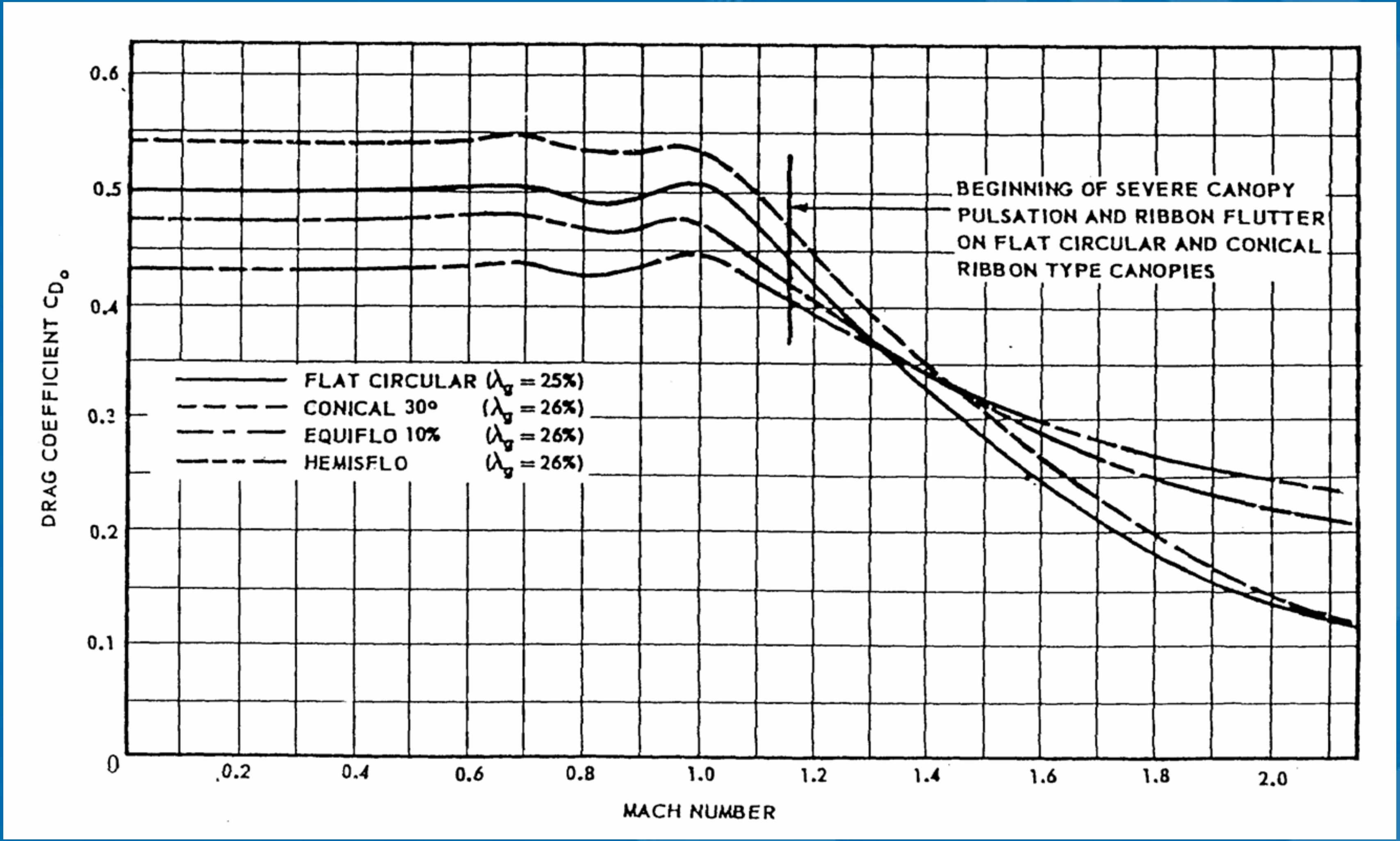
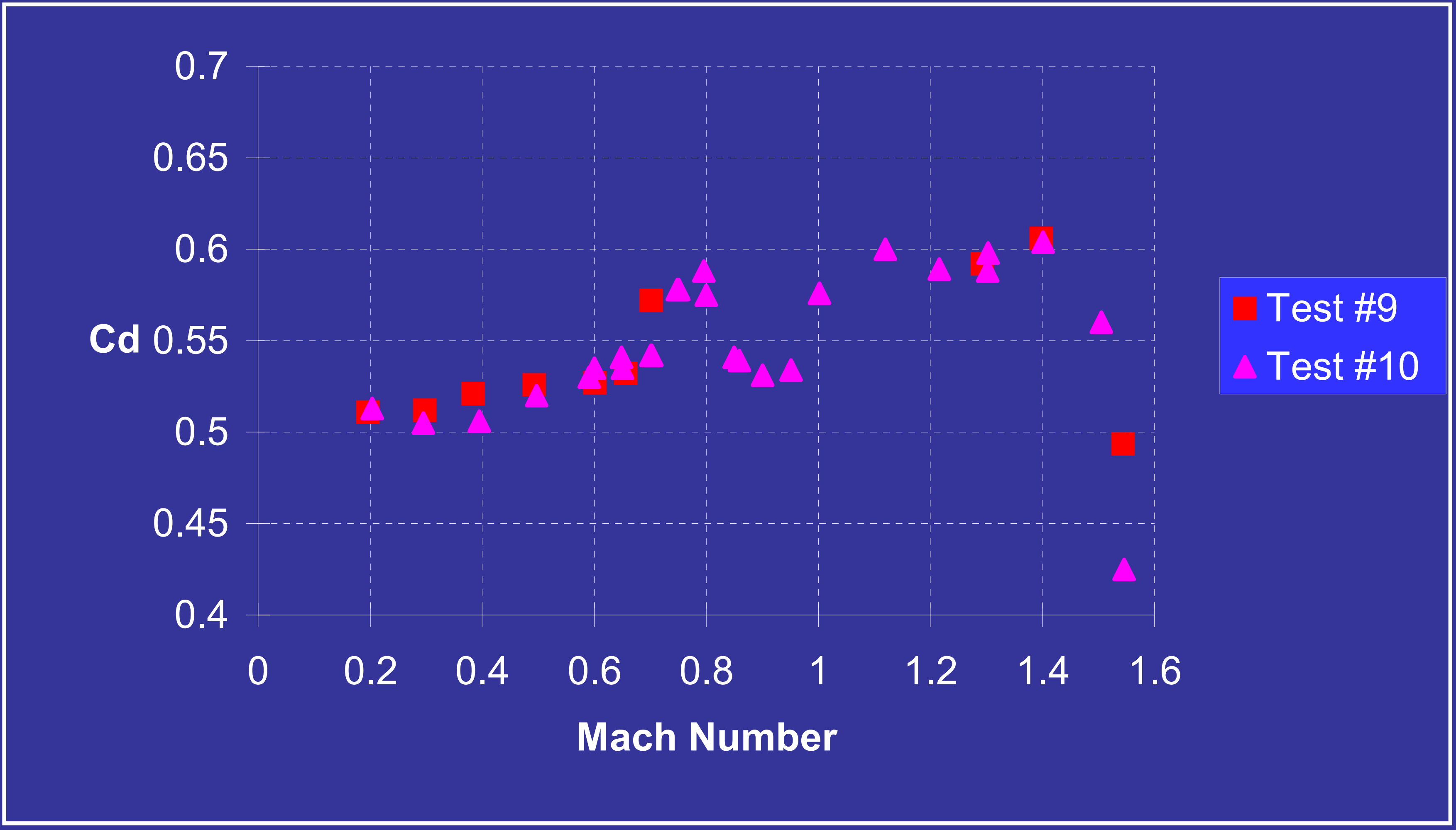
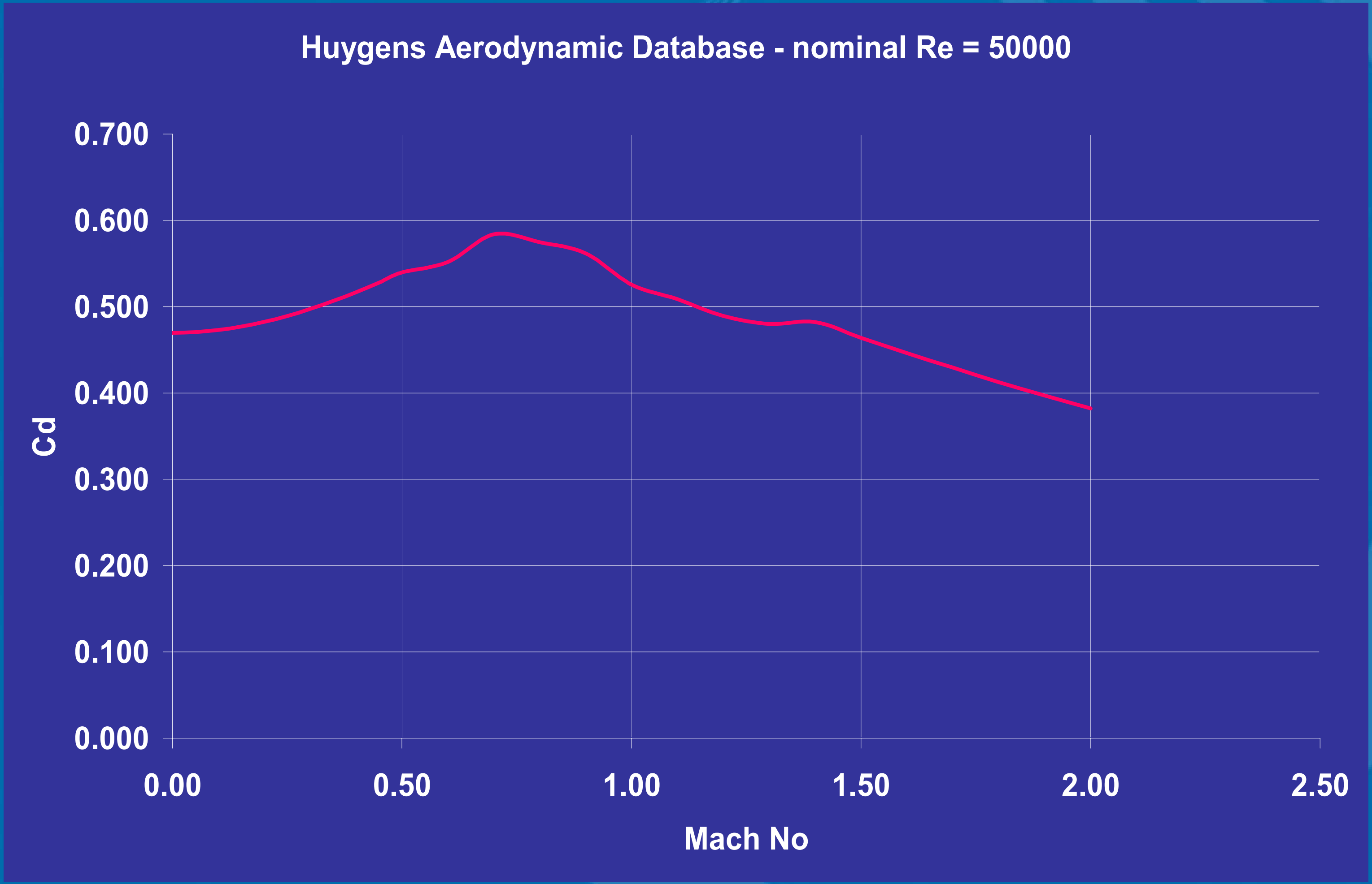
Ribbon parachute drag coefficient



Huygens DGB pilot chute ogive wake



Supersonic parachute behavior



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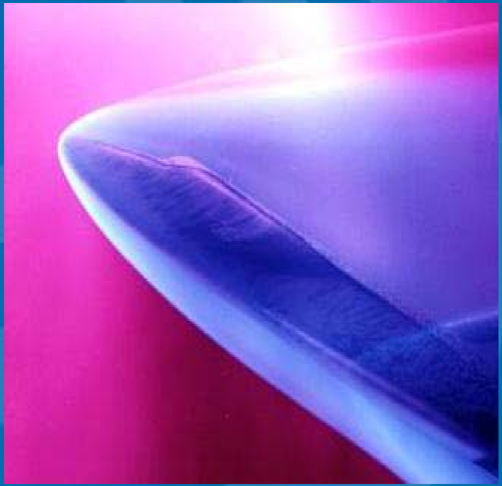
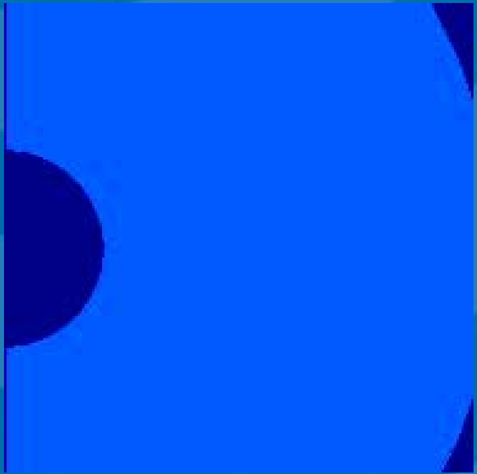
Supersonic parachute behavior

- Tests suggest that the performance of a parachute in transonic and supersonic flow is strongly influenced by:
  - canopy porosity
  - the size of the forebody (for axisymmetric bodies forebody diameter D_B) compared to the diameter of the parachute D0 represented by the ratio D_B / D_0
  - the distance between the base of the forebody and the parachute skirt (x_T) represented by the ratio x_T / D_B;
  - the shape of the forebody (streamlined or bluff);
  - line length;
  - detail canopy design;
  - Mach number

Supersonic Flow

- Compressibility
- High energy
  - energy transformations
- Shock waves
  - $a = (\gamma RT)^{0.5}$
  - M = v / a





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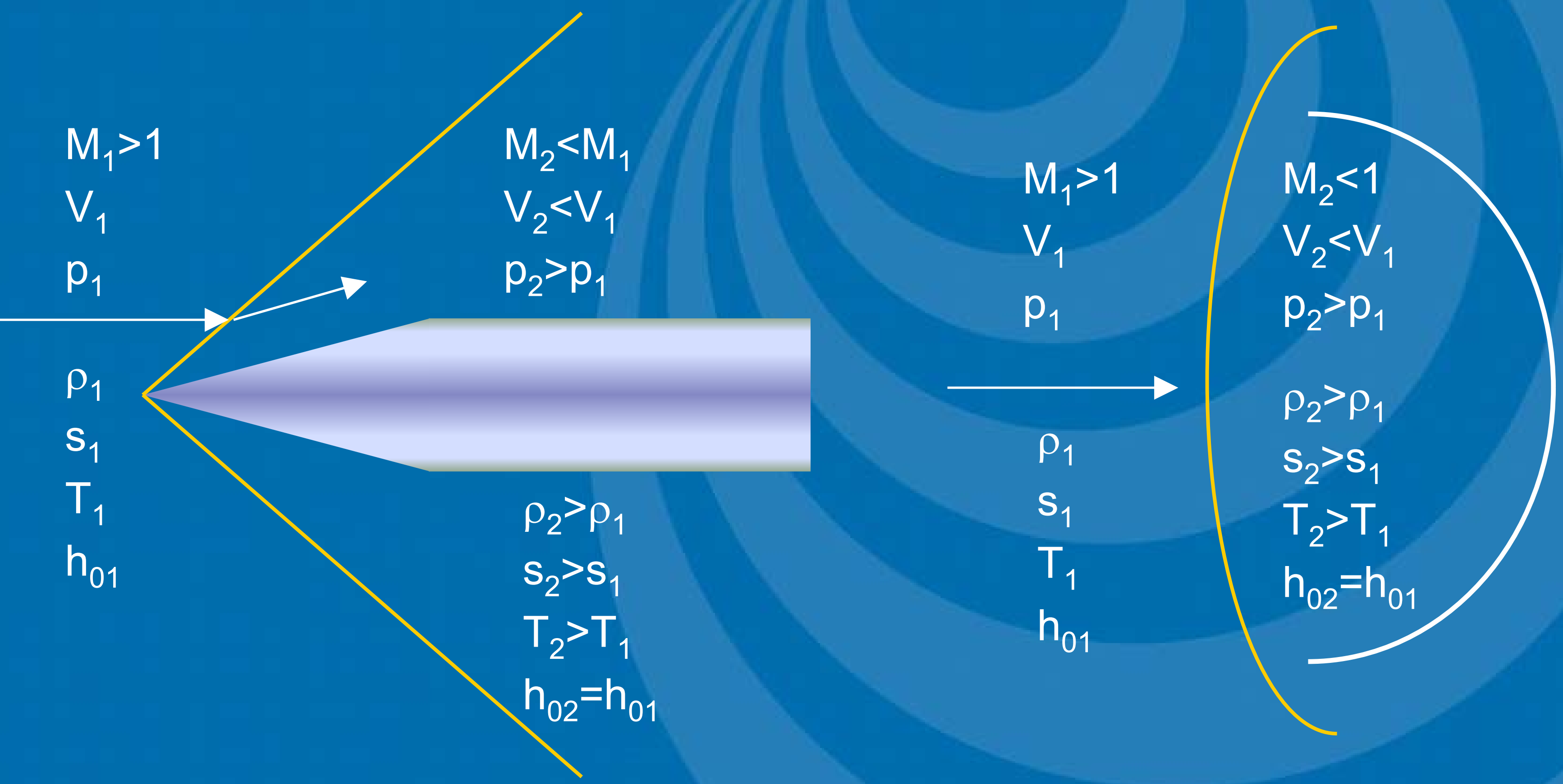
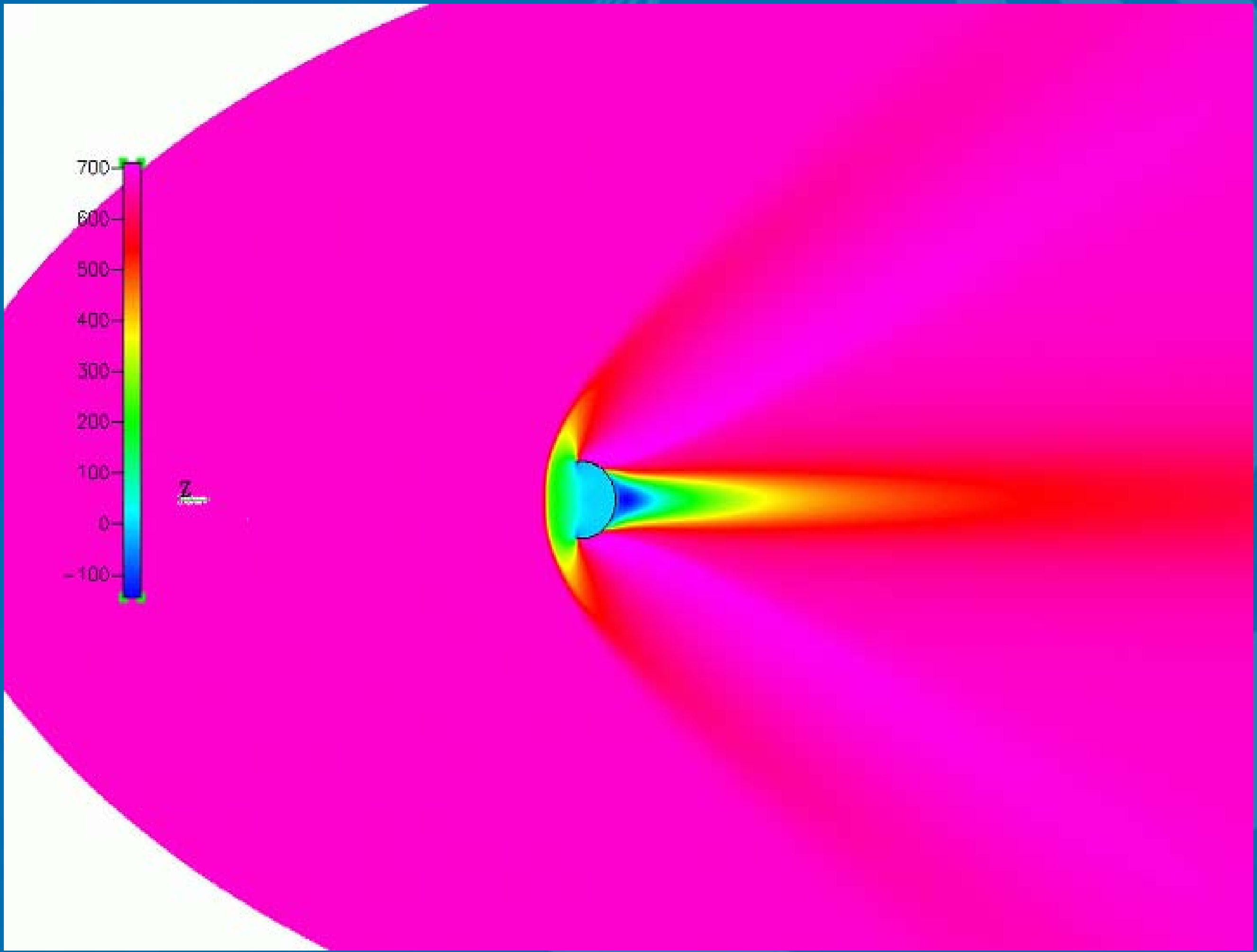
Property changes across attached and detached shock waves



Flow around a hollow hemisphere Mach 2.0



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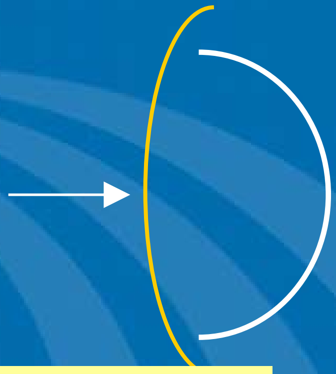
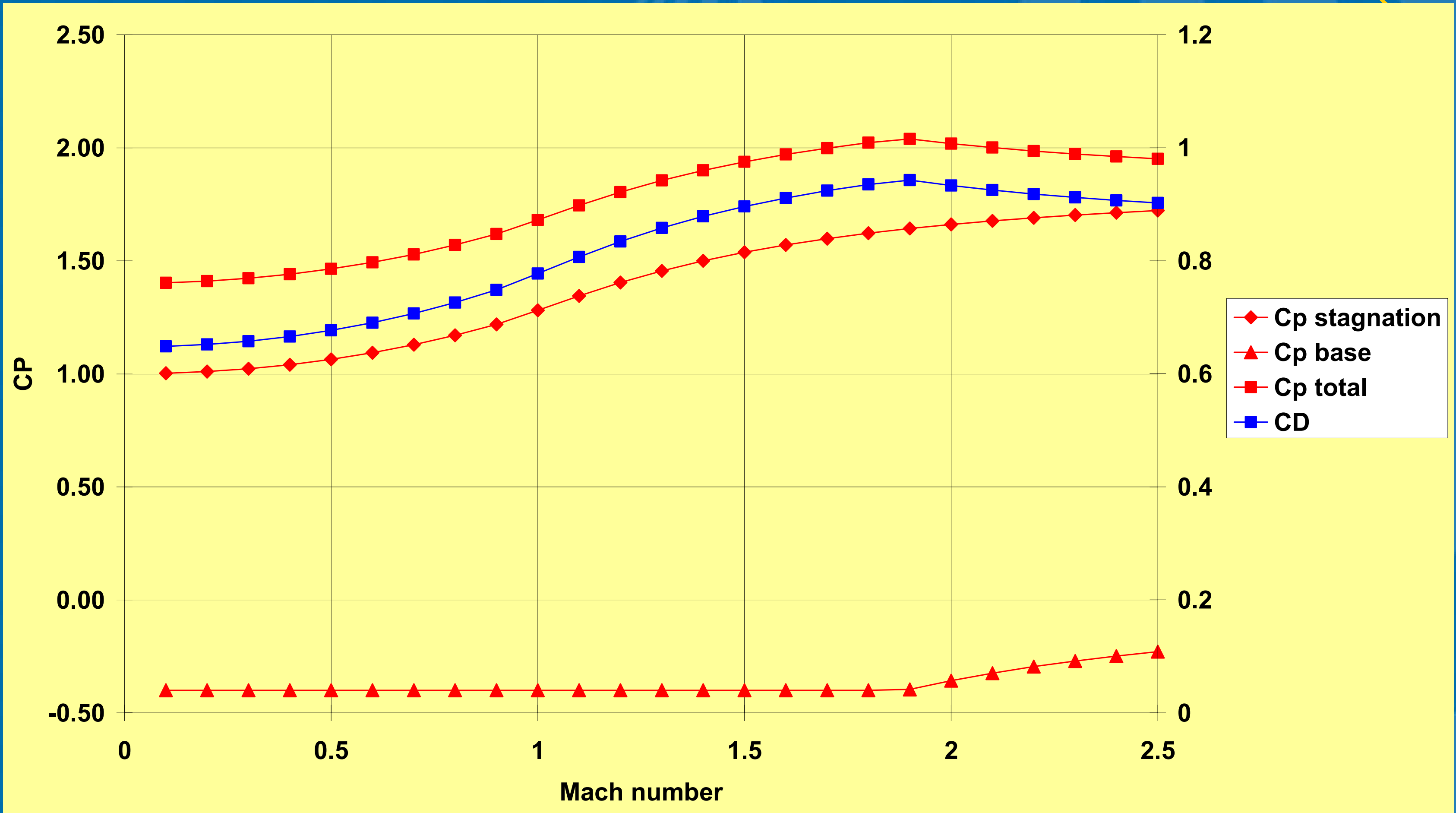
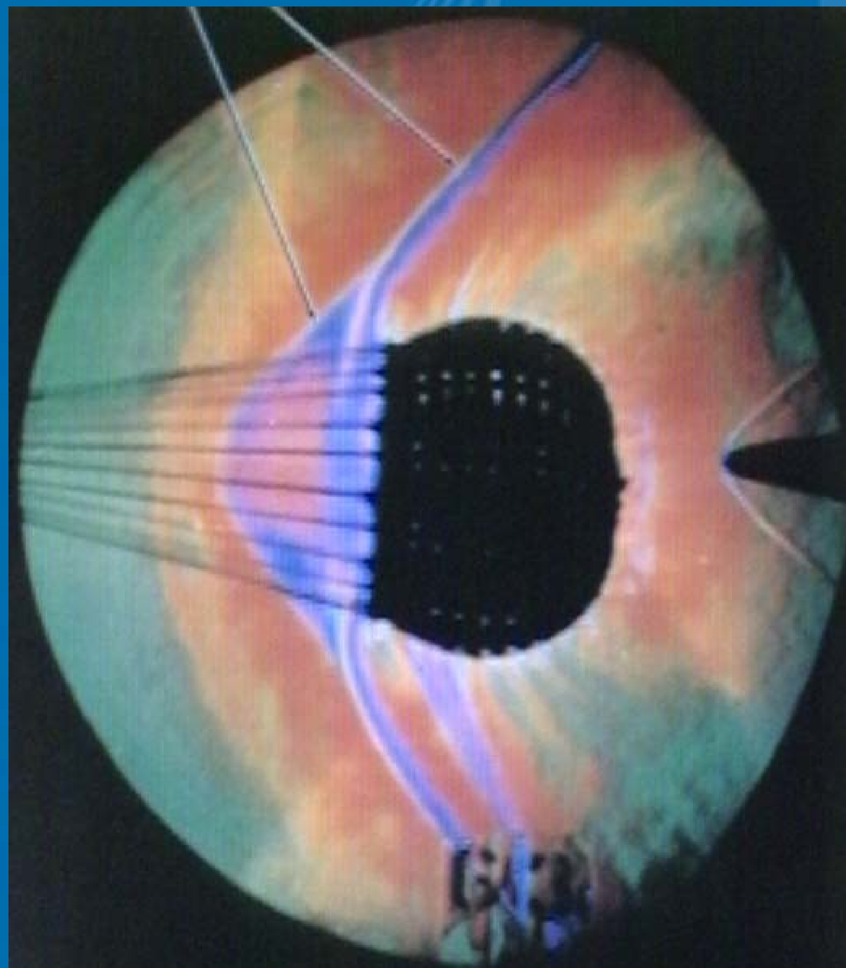
Drag of bluff body





Hemisflo - M 1.9

Shock waves



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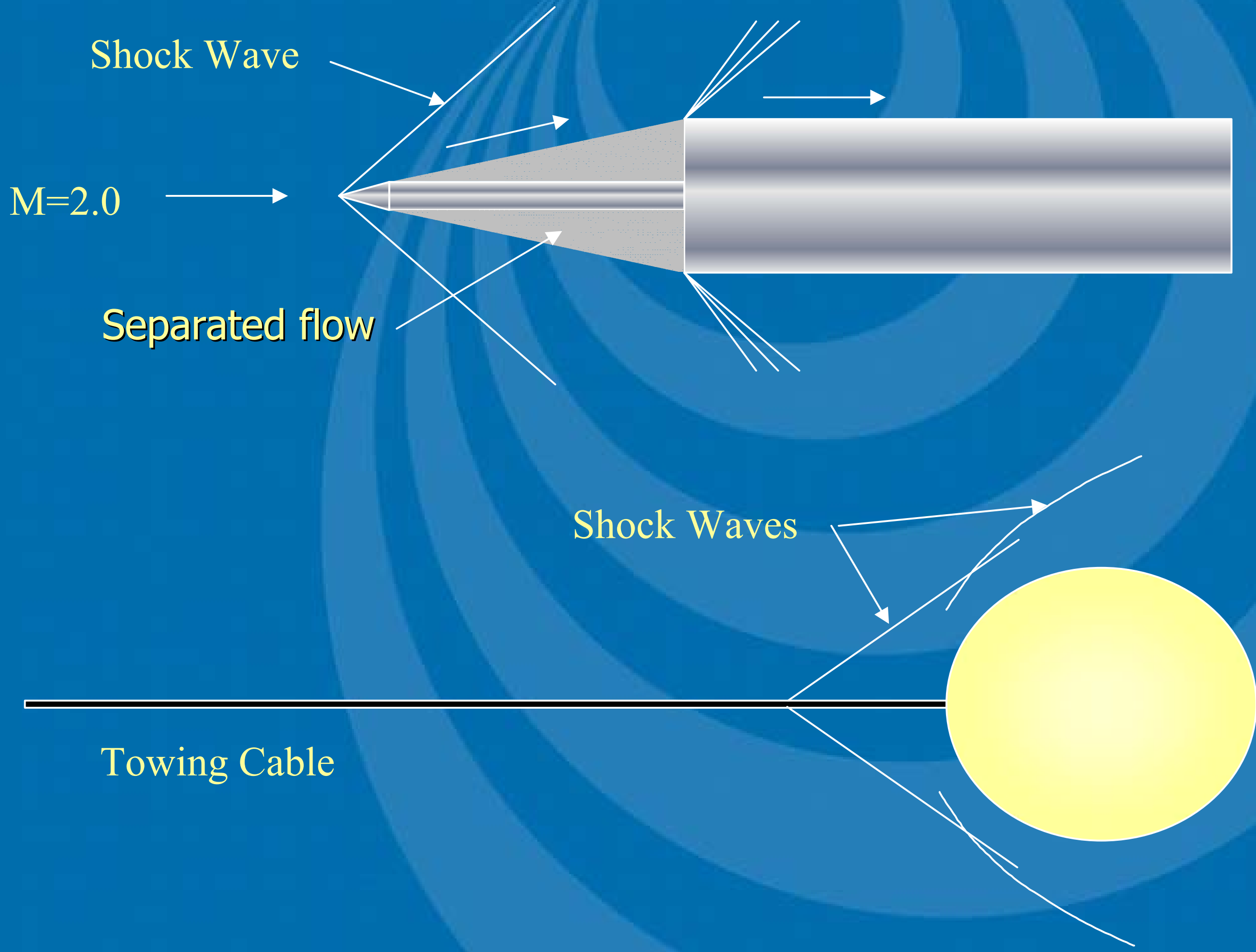
Spiked bodies



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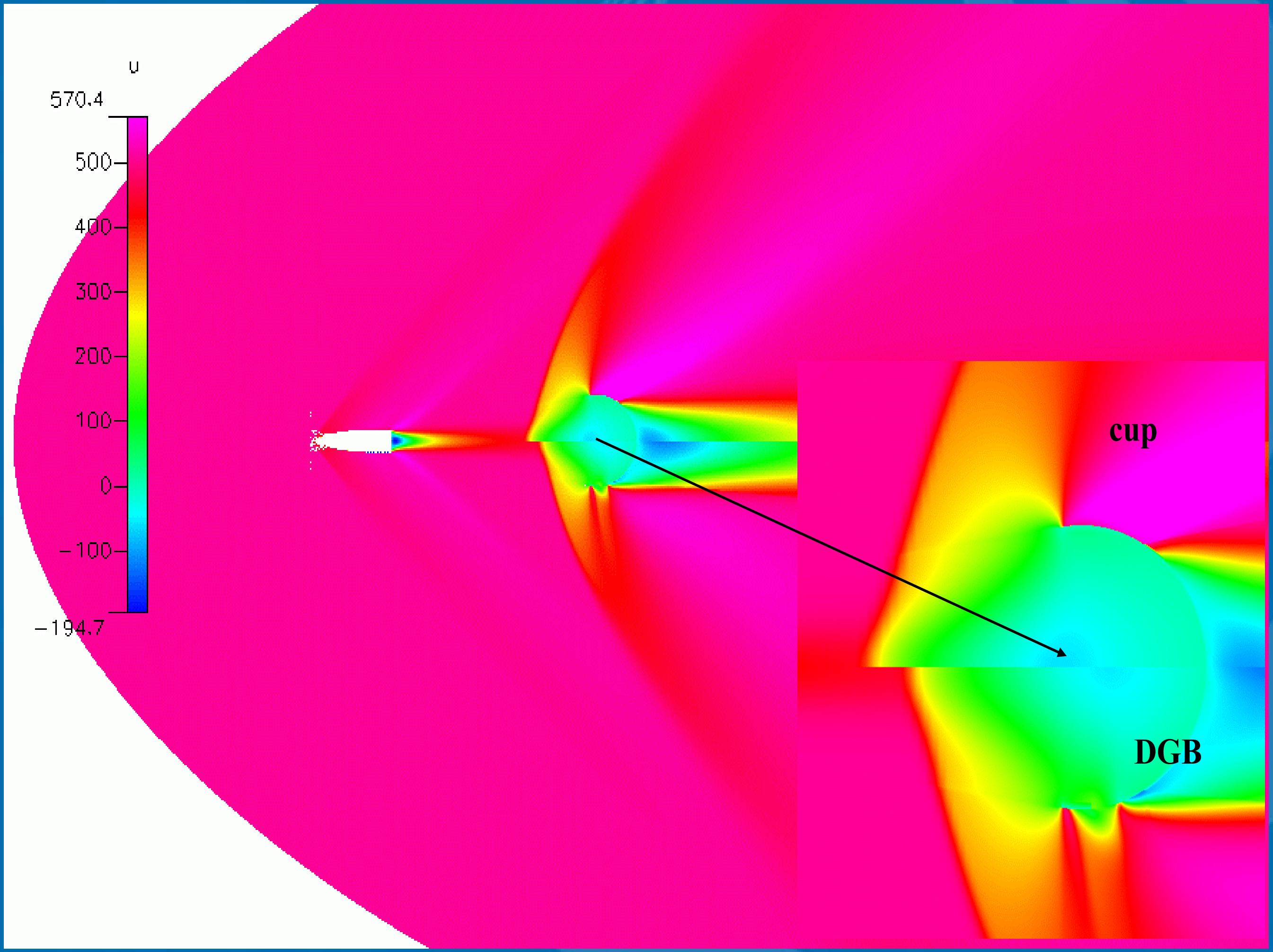
Flow around a hollow hemisphere and a DGB in the wake of a streamlined forebody M 2.0



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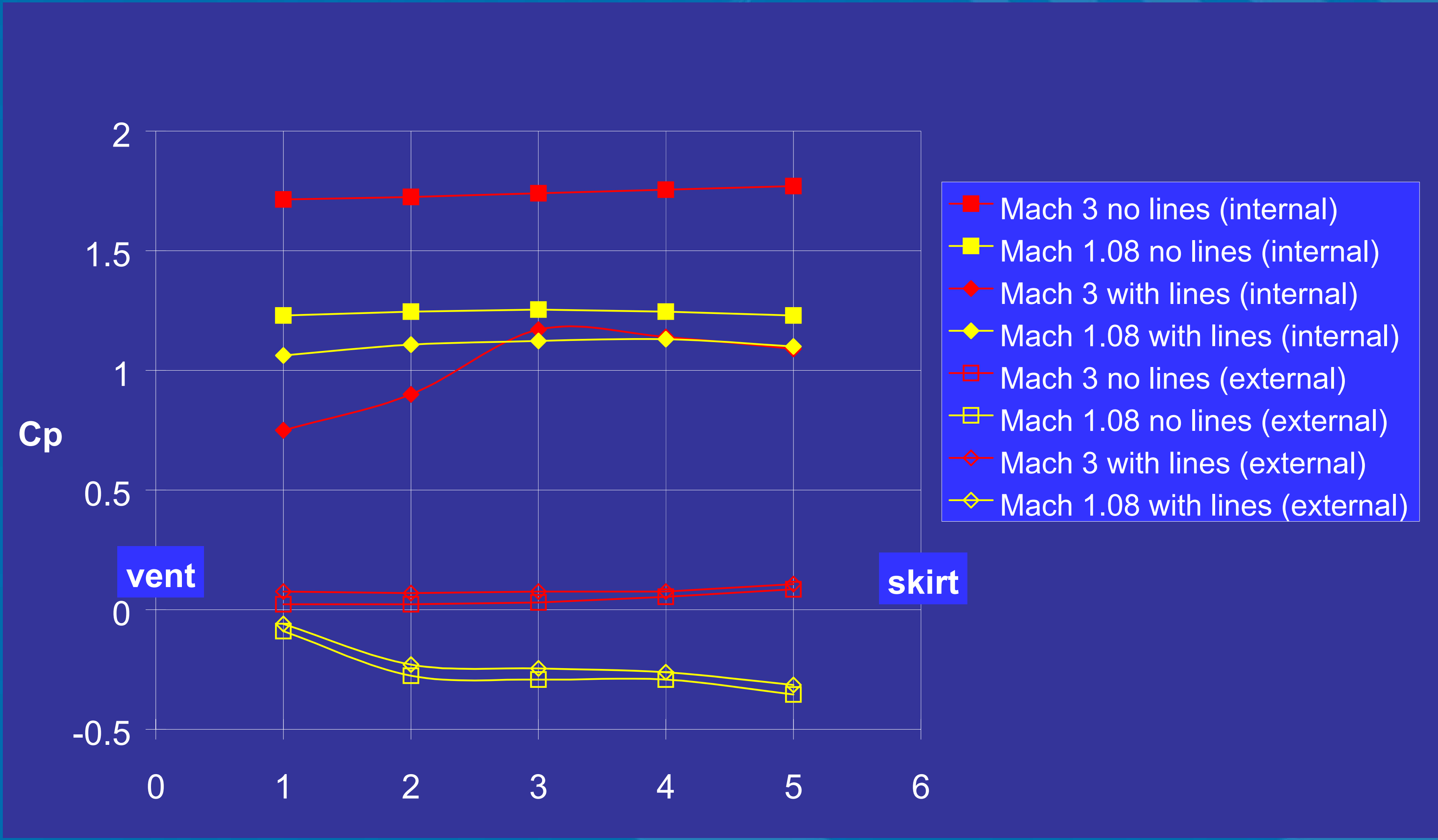
Parachute surface pressures



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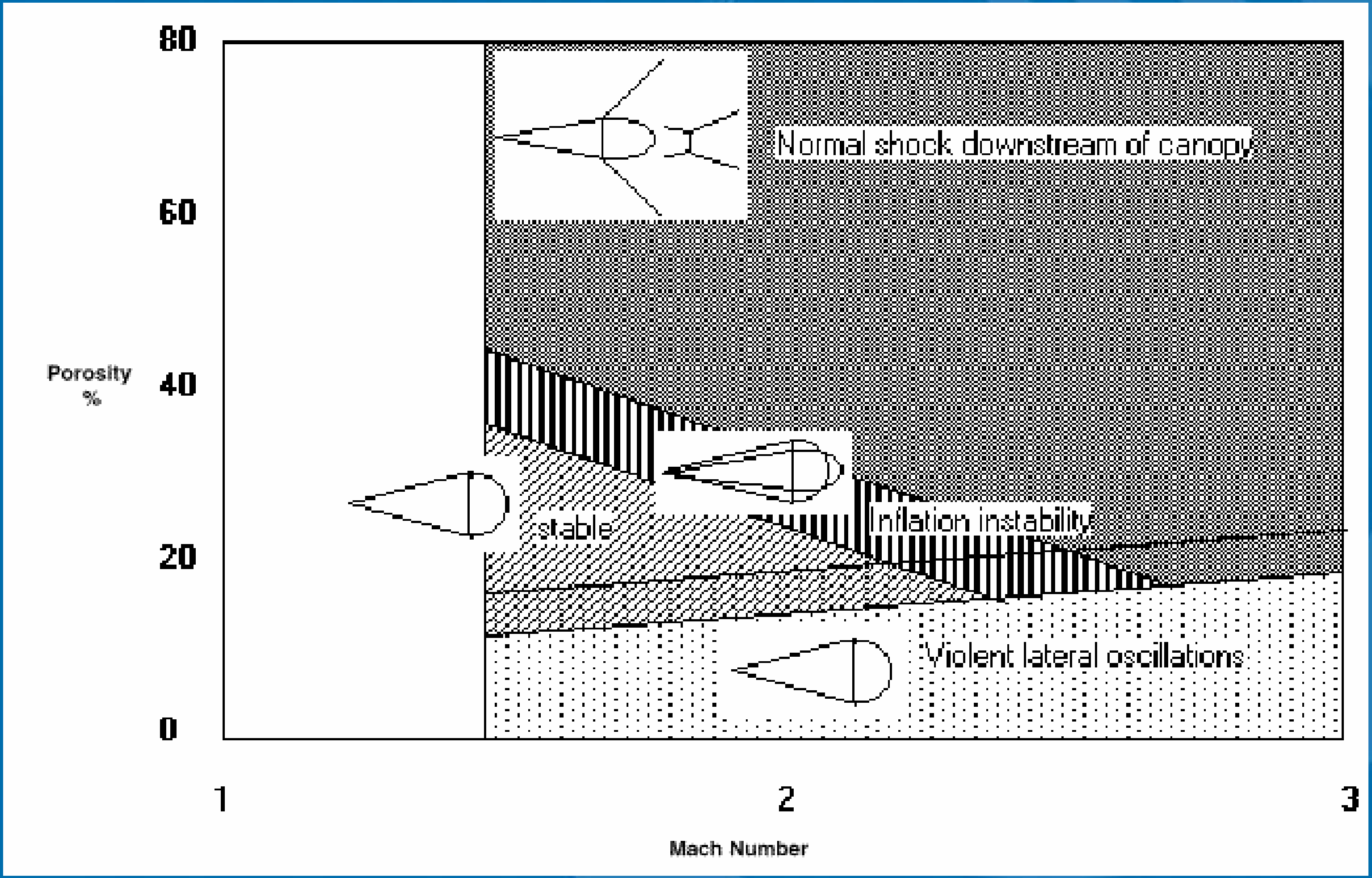
Supersonic parachute behavior



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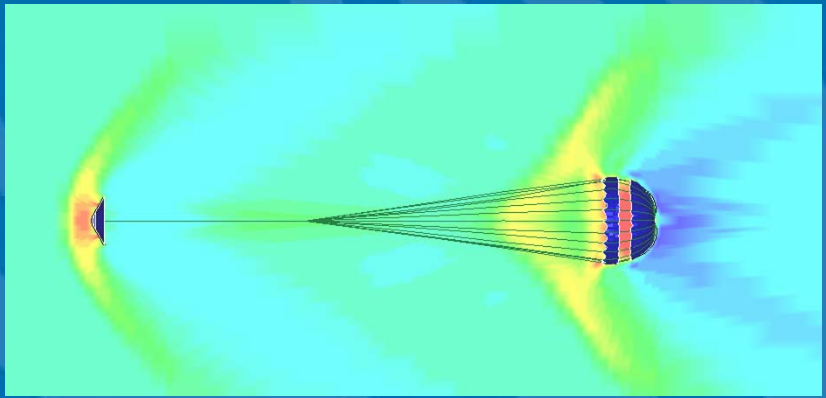
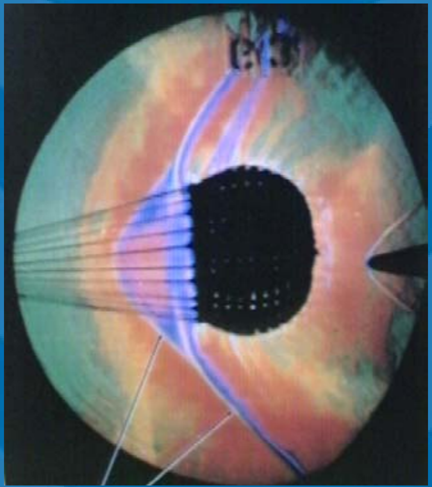
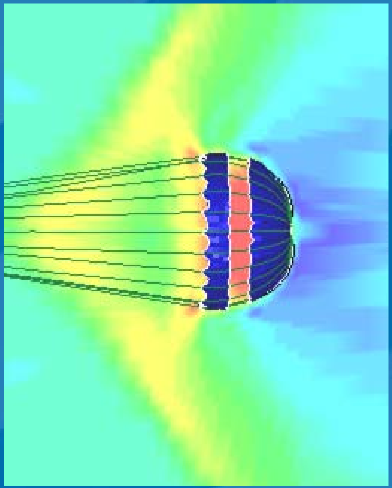
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

- Recent use of FSI starts to reveal complex flow physics around parachutes in supersonic flow
- ALE code







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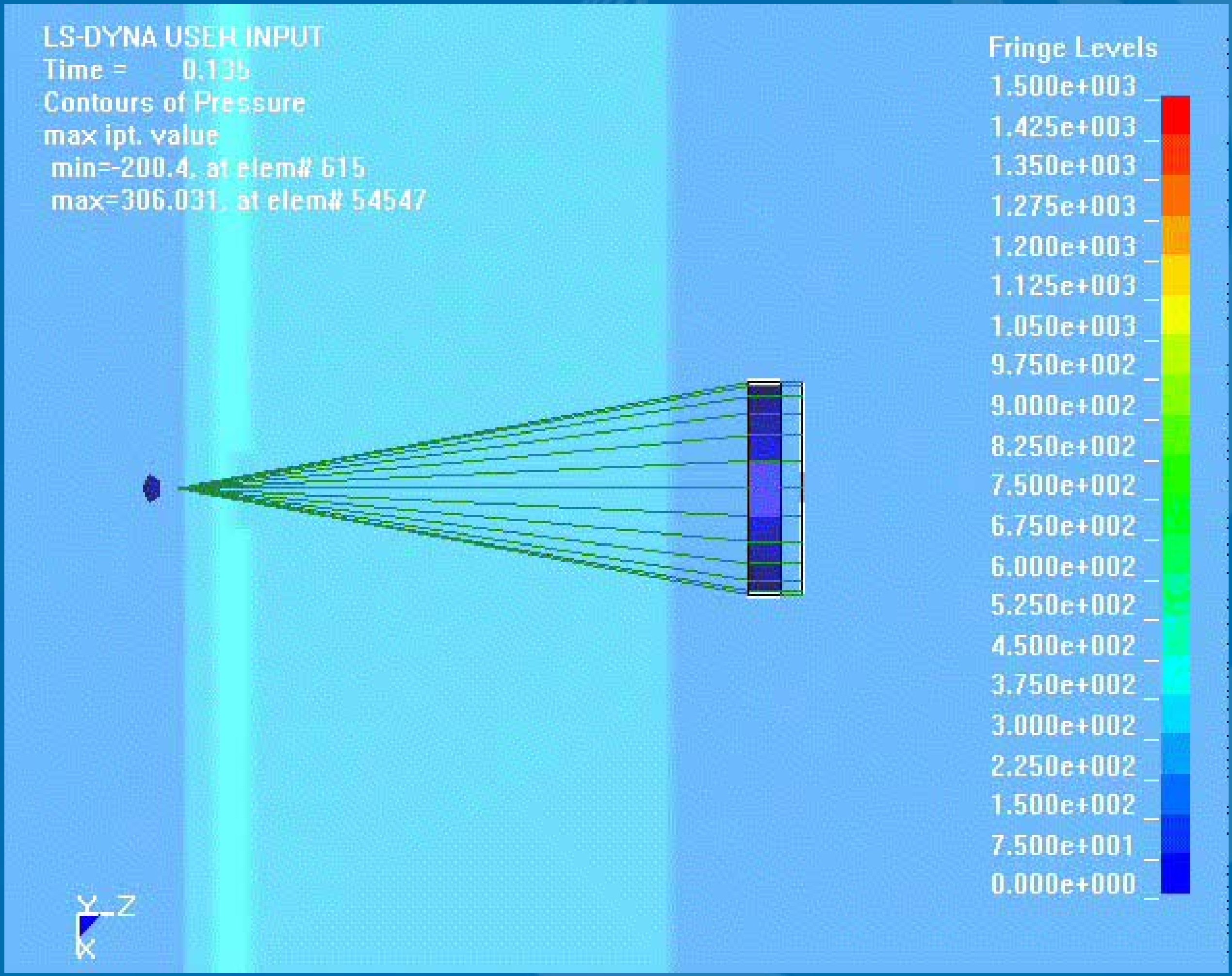
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P



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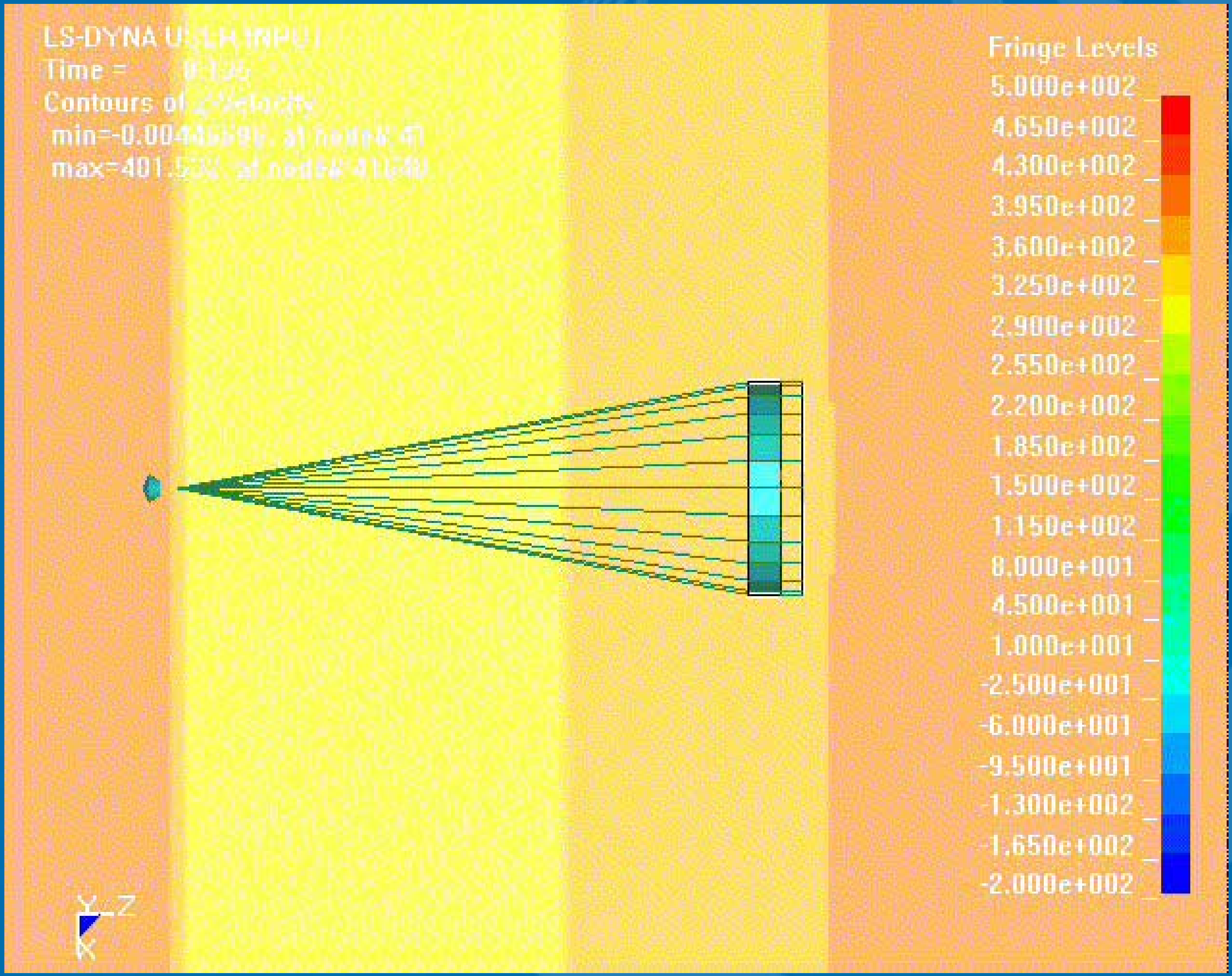
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P



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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

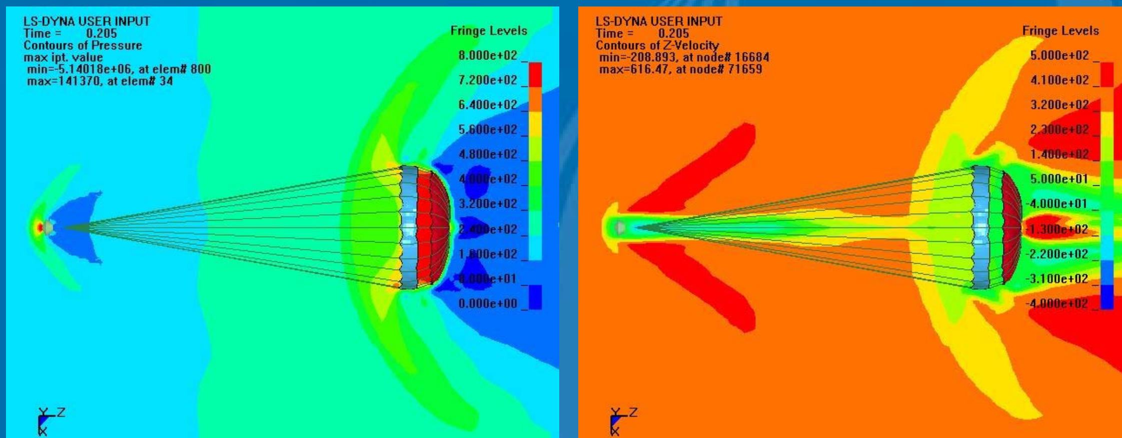

Figure 6a. *t* = 0.205 s

- high pressure area in canopy
- strong curved shock ahead of canopy
- probe wake flows into the canopy

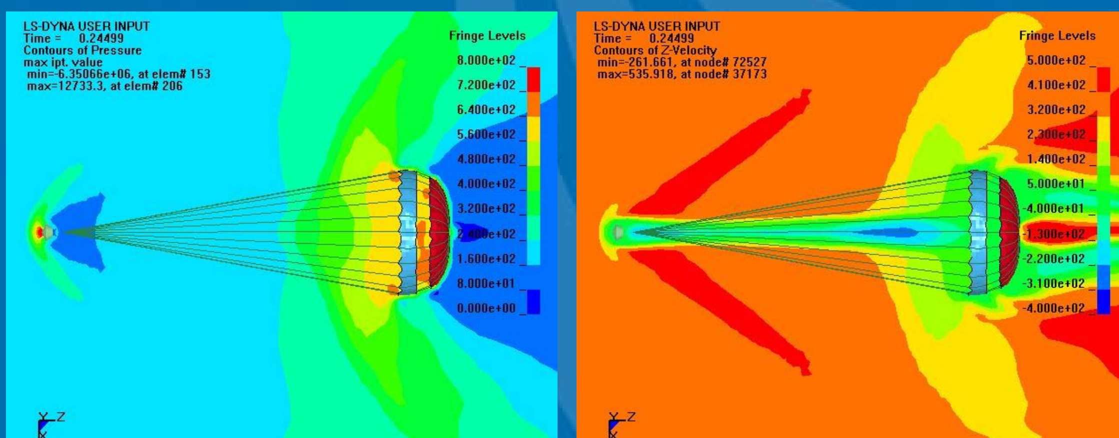

Figure 6b. *t* = 0.245 s

- shock ahead of the canopy more conical
- reverse flow from the high pressure area within canopy up the probe wake

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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

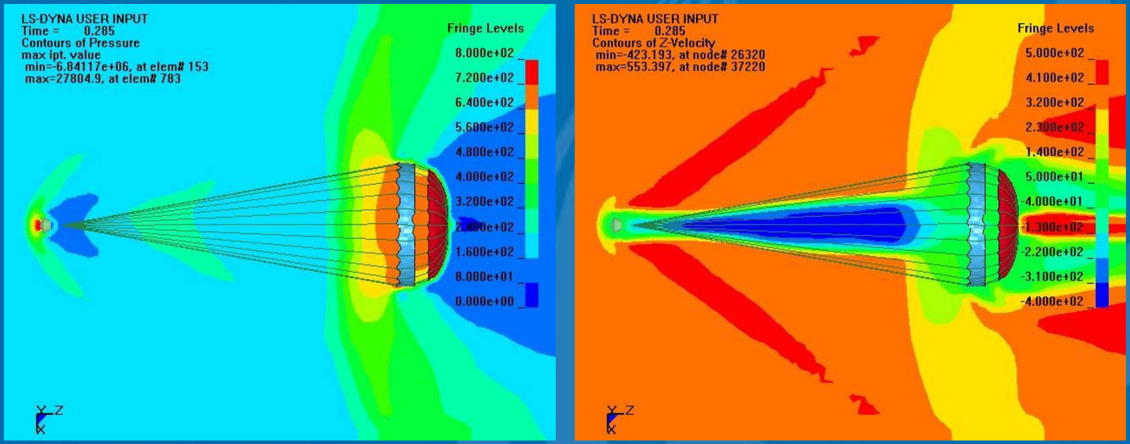

Figure 6c. *t* = 0.285 s

shock very conical just behind the base region of the probe

large volume of reverse flow moving towards the base of the probe

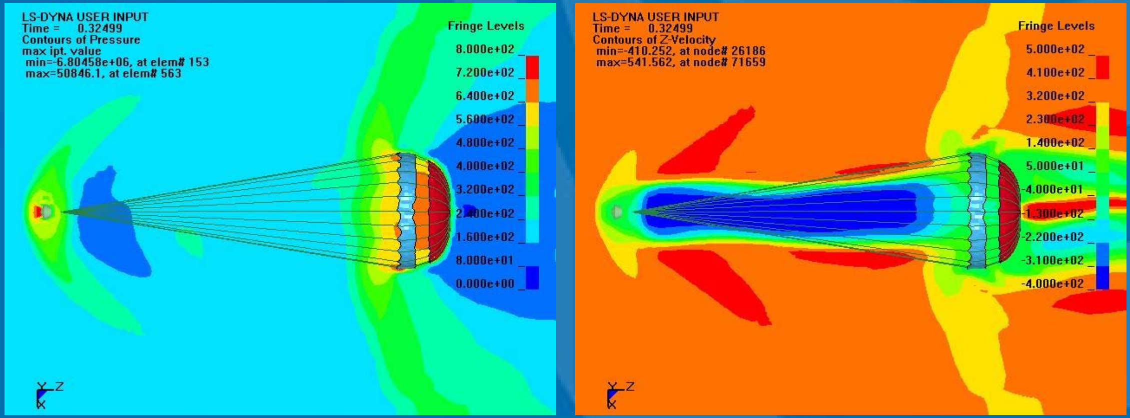

Figure 6d. *t* = 0.325 s

reverse flow grown further and reached base of the probe

shock ahead of the probe is modified and trailing shock is disrupted

pressure in the canopy is reduced

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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

- reverse flow unstable
- probe base flow completely disrupted - region of high pressure behind probe
- parachute immersed low energy, subsonic flow
- pressure inside the canopy is now low

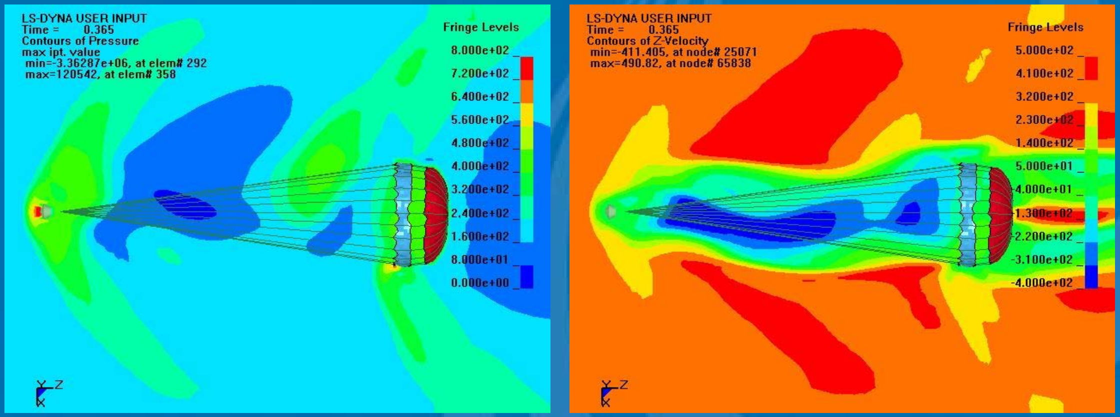

Figure 6e. *t* = 0.365 s

- pressure in canopy very low
- canopy starts to collapse
- flow ahead of the canopy confused and subsonic

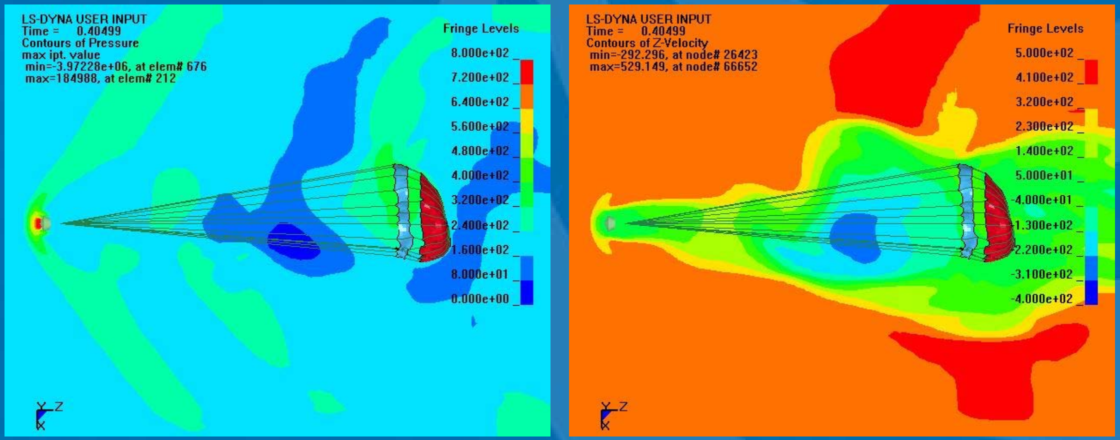

Figure 6f. *t* = 0.405 s

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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

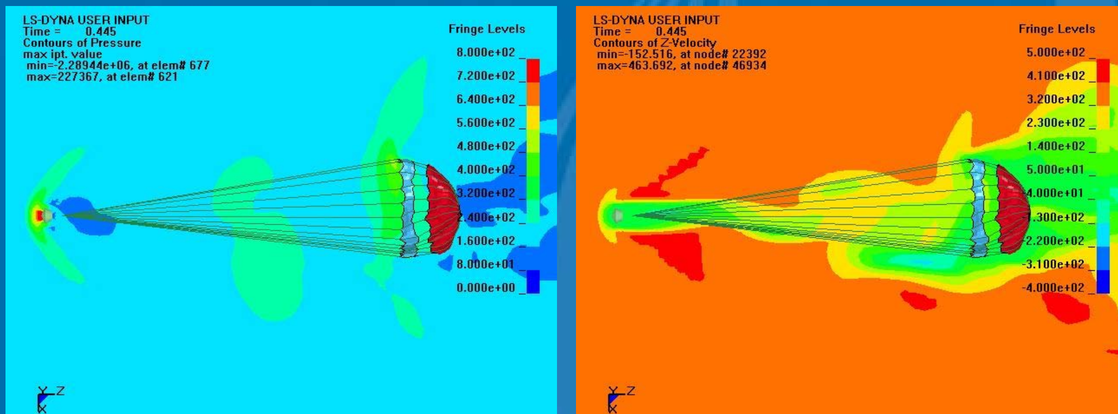

Figure 6g. *t* = 0.445 s

flow around the probe reestablishing

low energy flow ahead of the canopy moves off downstream

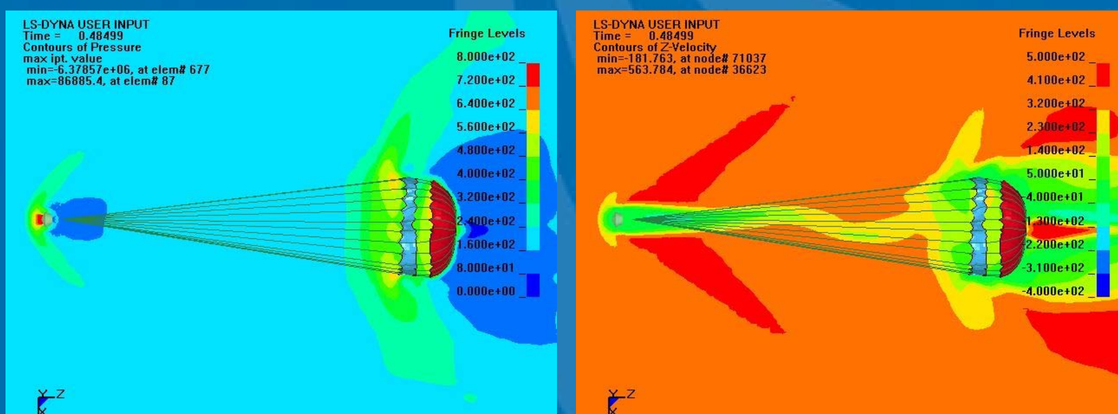

Figure 6h. *t* = 0.485 s

flow around the probe reestablished

pressure increases in canopy

canopy reinflates

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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

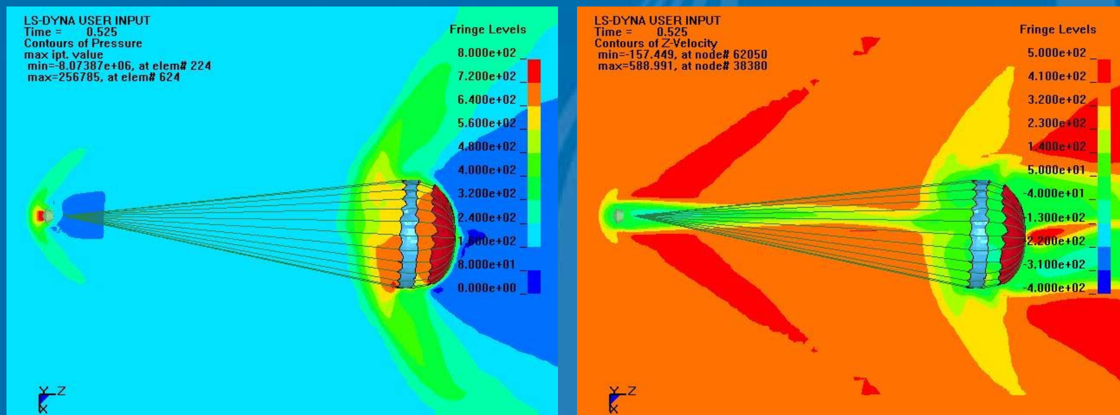

Figure 6i. *t* = 0.525 s

clear shock pattern around the probe

strong curved shock ahead of the canopy

high pressure region within the canopy

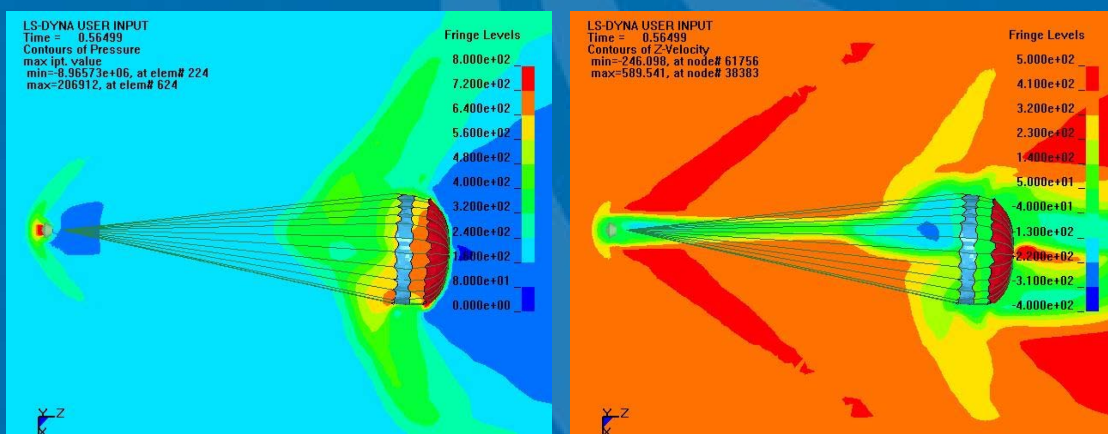

Figure 6j. *t* = 0.565 s

shock ahead of the canopy more conical

reverse flow from the high pressure area within canopy up the probe wake

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Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 3.1 D_P

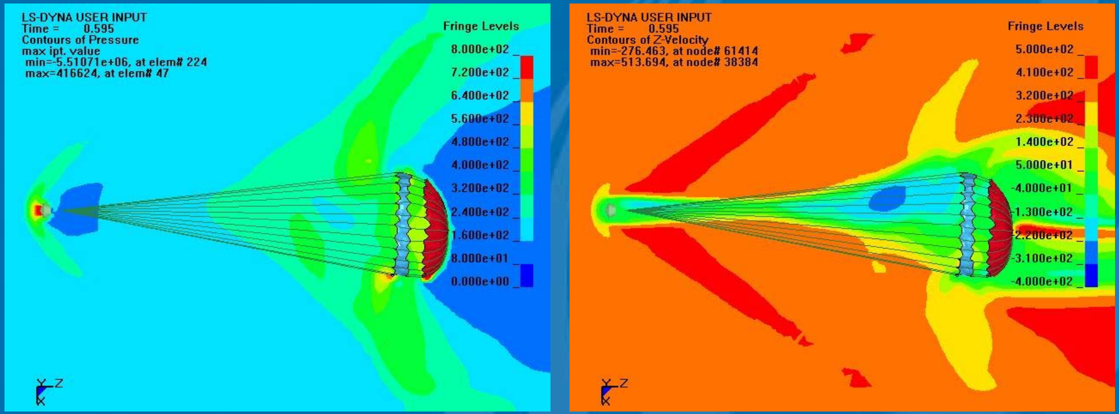

Figure 6k. *t* = 0.595 s

conical shock moves towards probe

reverse flow established in wake

cycle repeating

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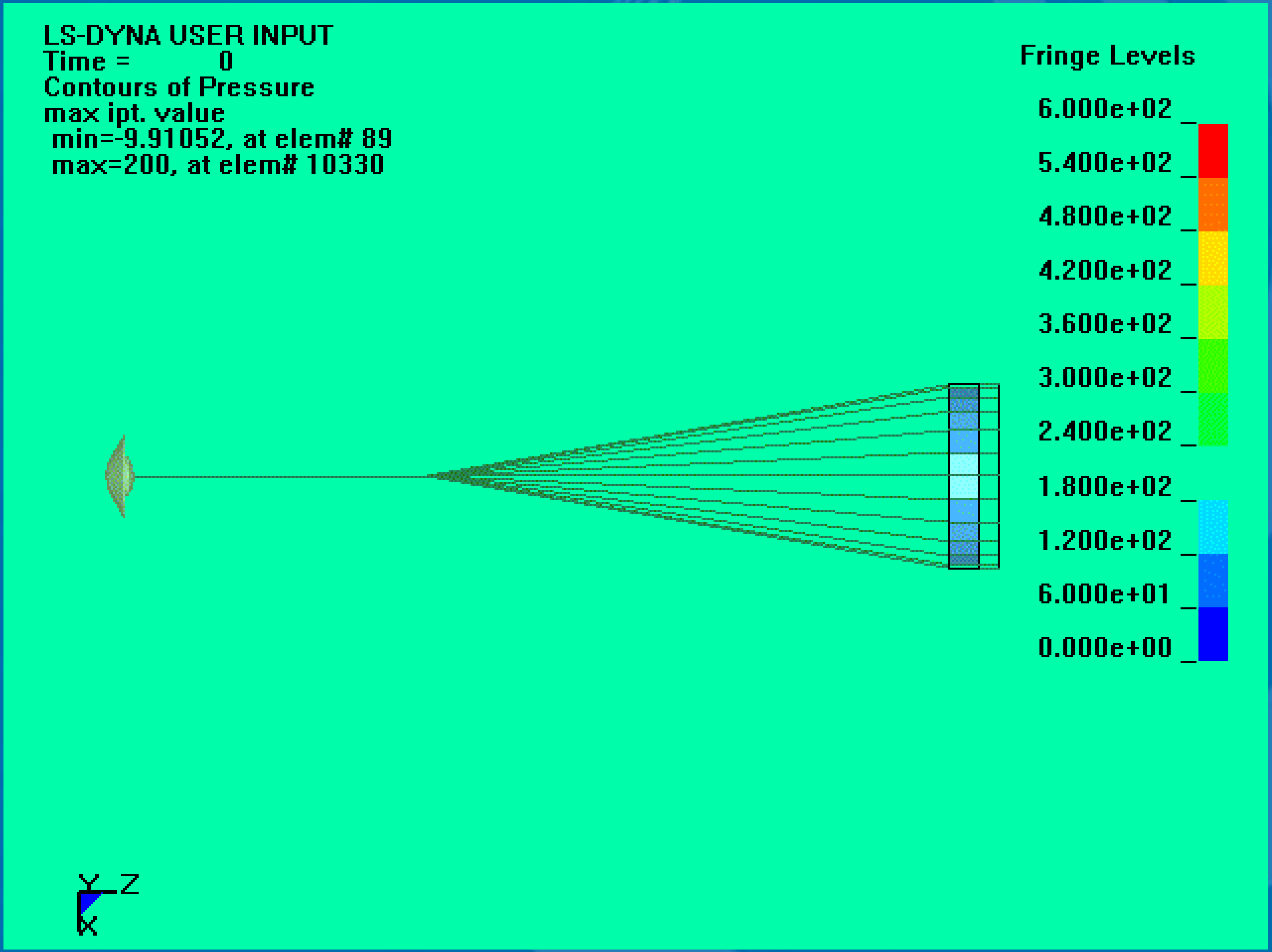
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P



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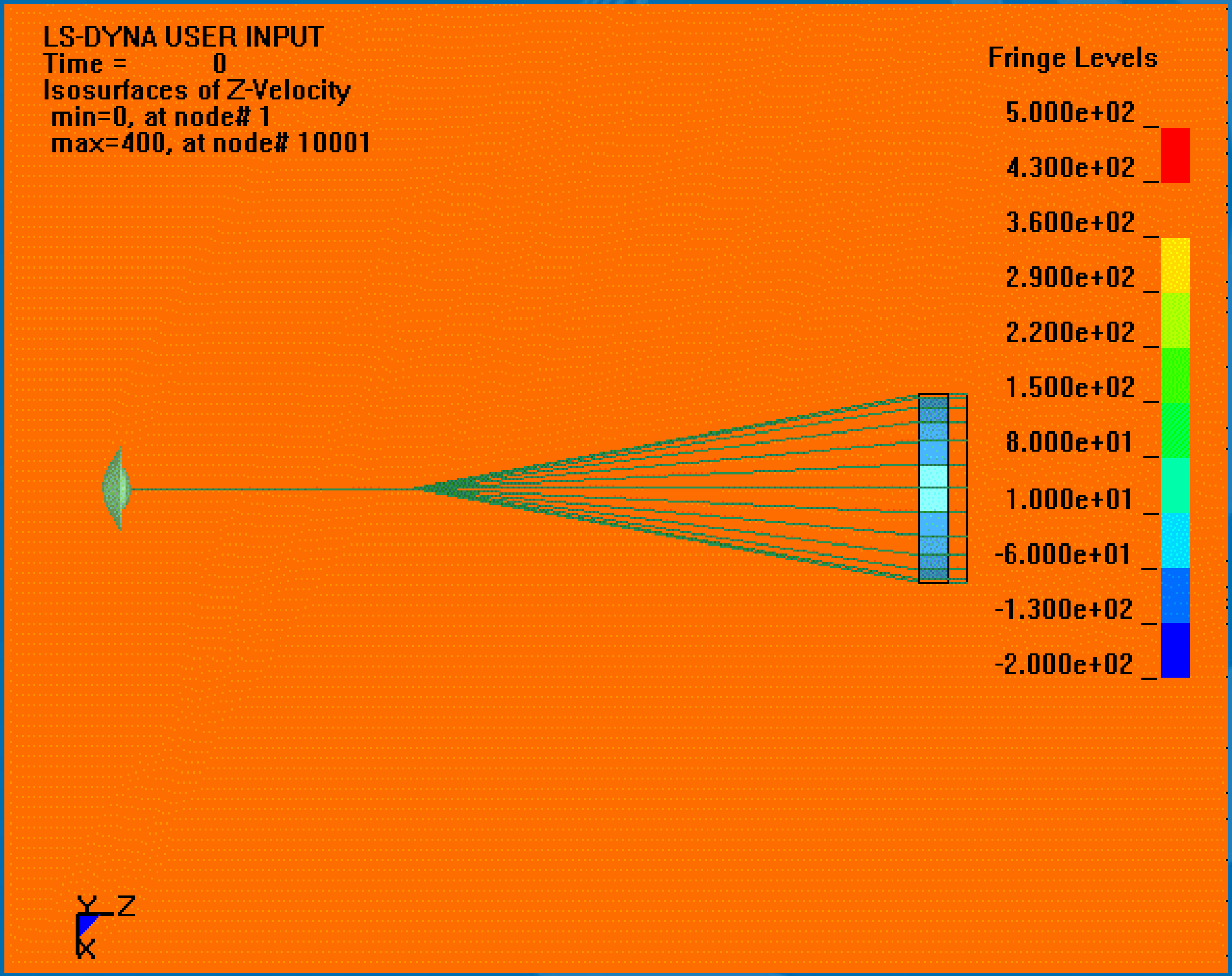
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P



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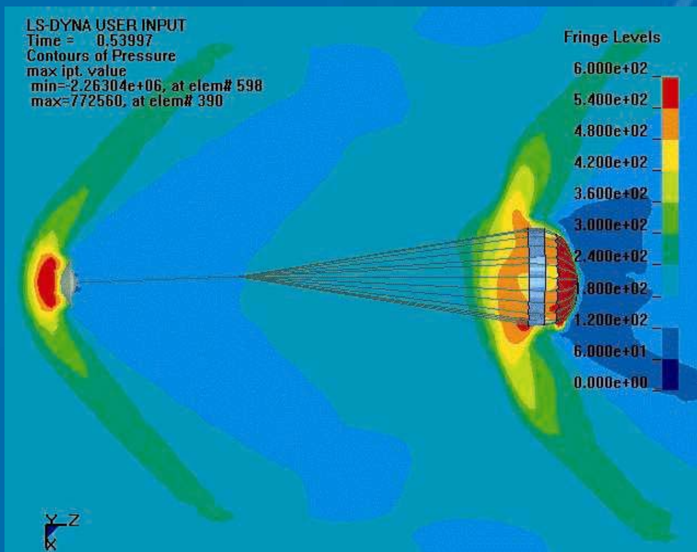
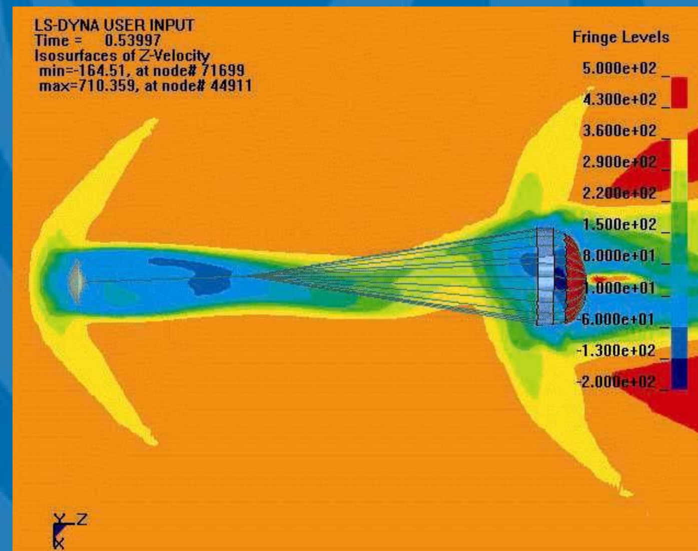
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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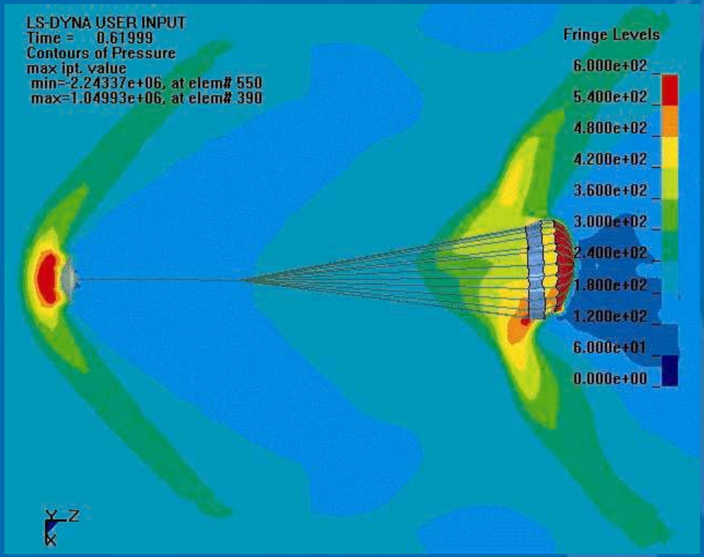
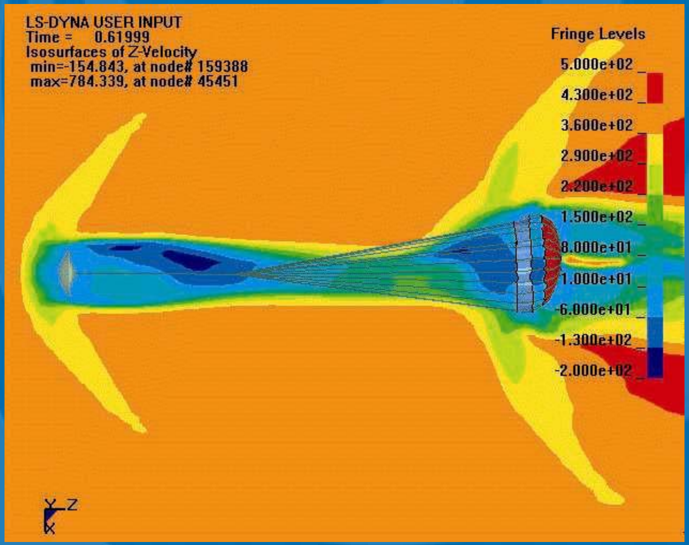
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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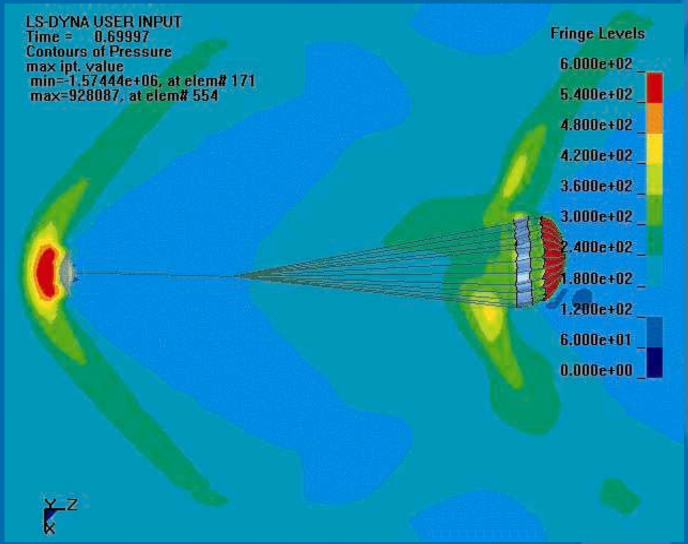
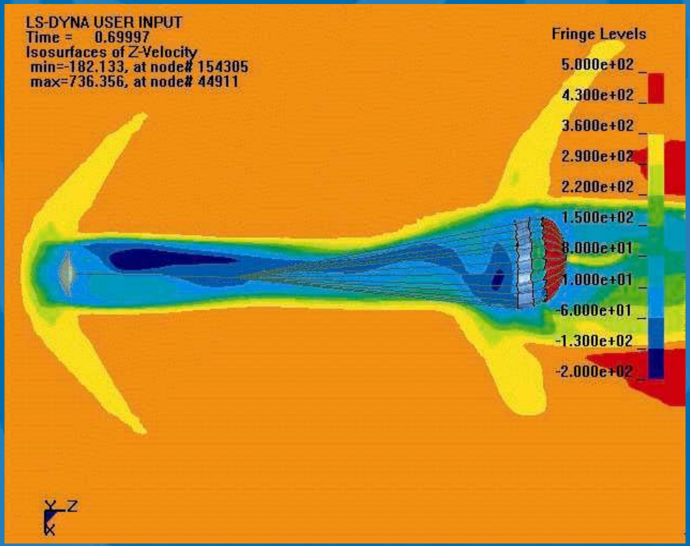
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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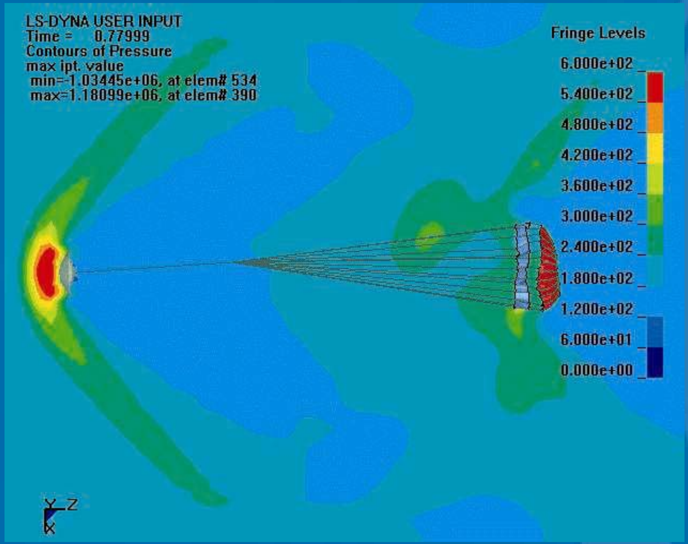
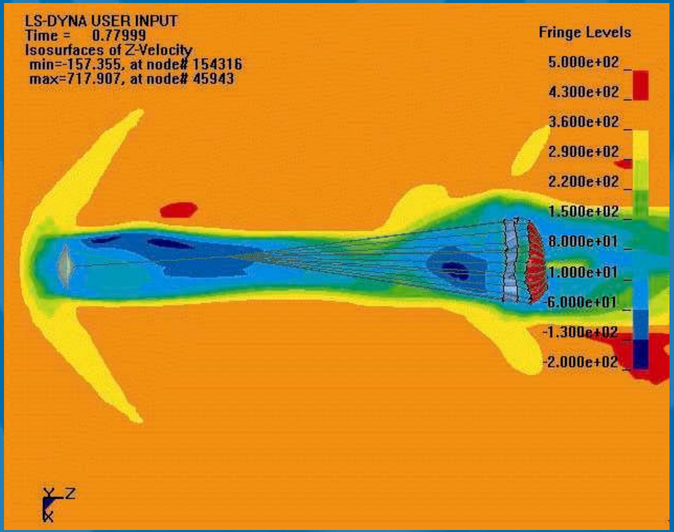
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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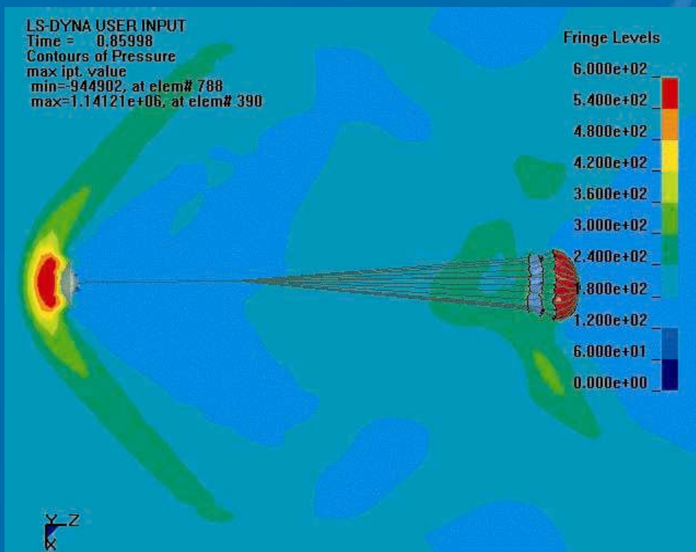
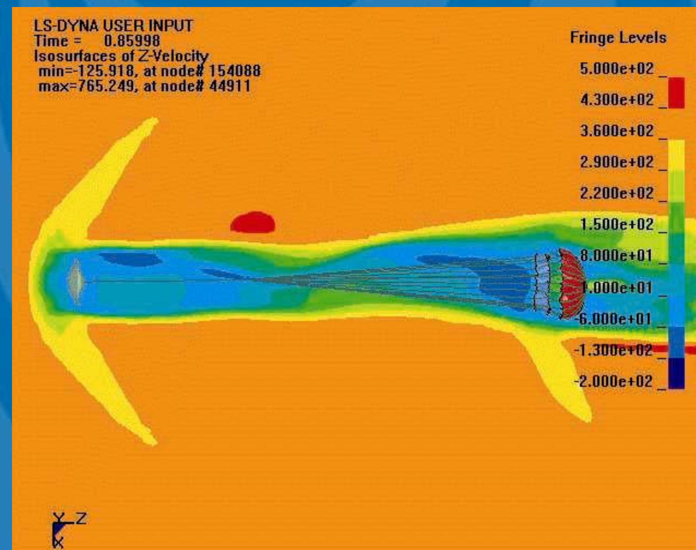
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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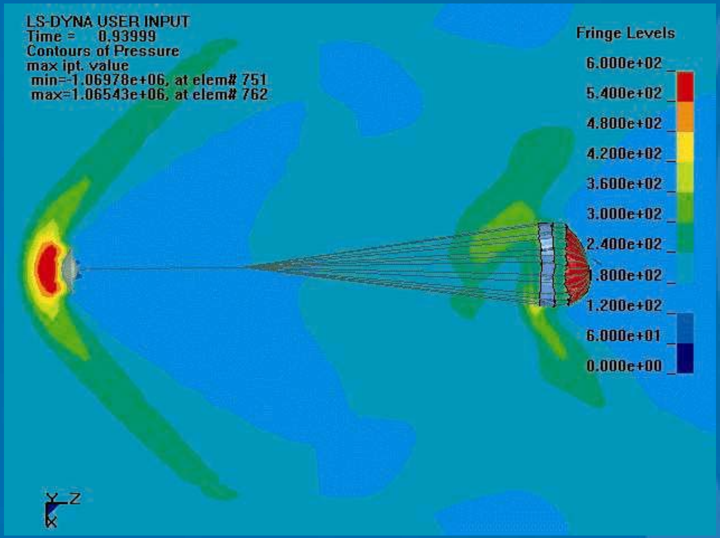

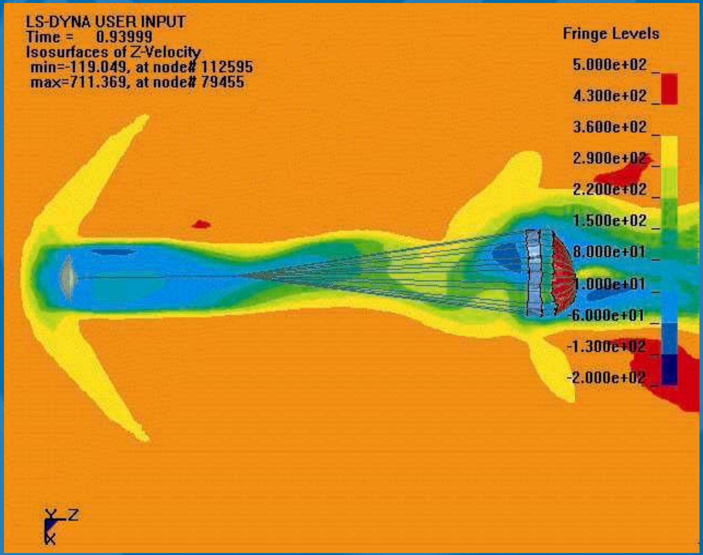

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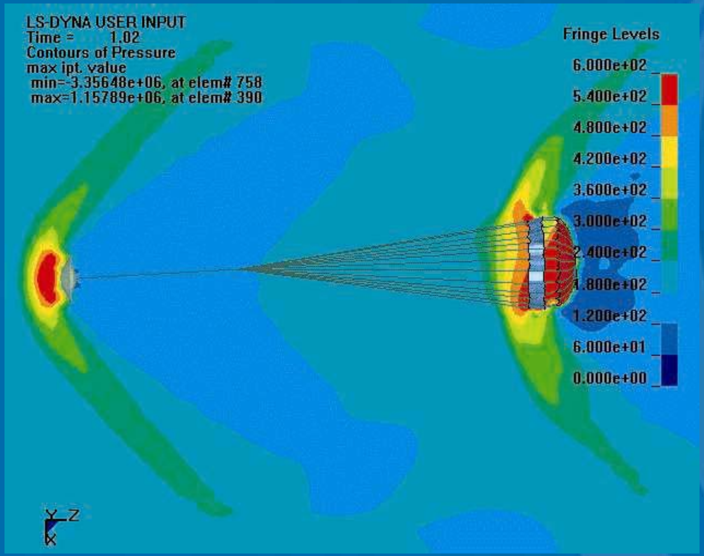
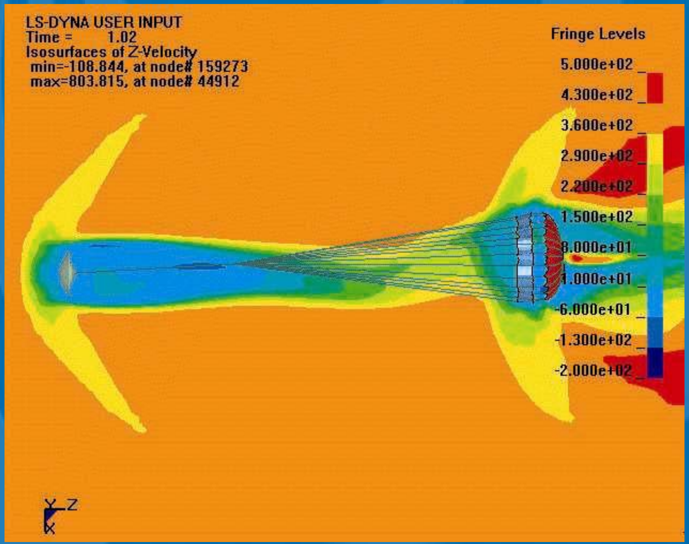
Flow around a disk-gap-band parachute at Mach 1.5, trailing distance 4.8 D_P





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Supersonic flow around parachutes

- Dominated by interaction with viscous wake
- At low supersonic Mach number conical shock forms and reduces drag
- At higher Mach number forebody base flow is disrupted cyclically and parachute pulsation commences with large drag loss

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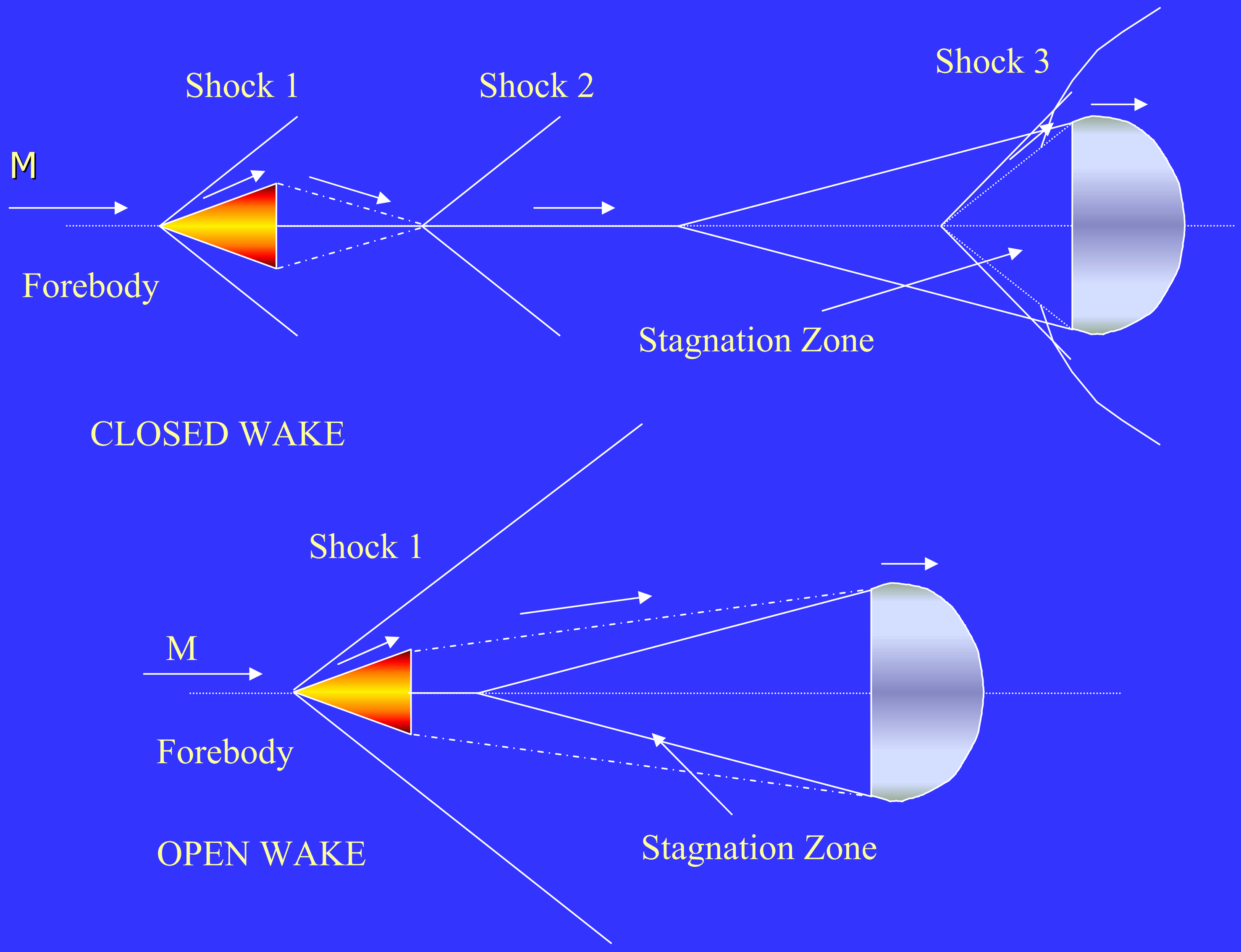
Wake effects



Wake modification

- Accepted wisdom: $x_T > 10D_B$
- Moseev's criterion: $x_T > 1.5D_B + 2.5D_P$
- Current work would suggest be 4-5 parachute diameters behind the payload!
  - Galileo was 5 D_P
  - Huygens is 4.9 D_P
  - Viking was 2.7 D_P

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Ribbon flutter

- modified pressure distribution acting on a flexible canopy causes mouth area to vary
- for flat circular or conical ribbon designs if the canopy flying diameter reduces then there is excess material at the canopy skirt
- excess material may be subject to flutter
- may either be lifted out from the axis of the canopy or pushed inwards depending on incidence
- oscillations are set up under certain conditions causing variations in mouth diameter
- these should not be confused with the pulsation

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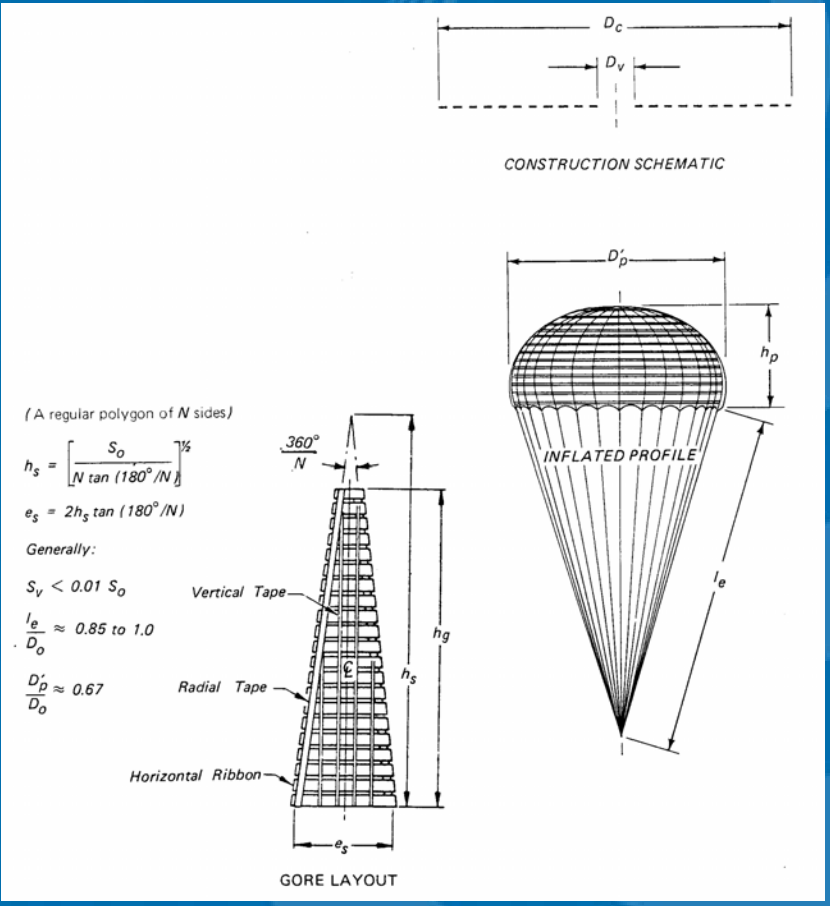
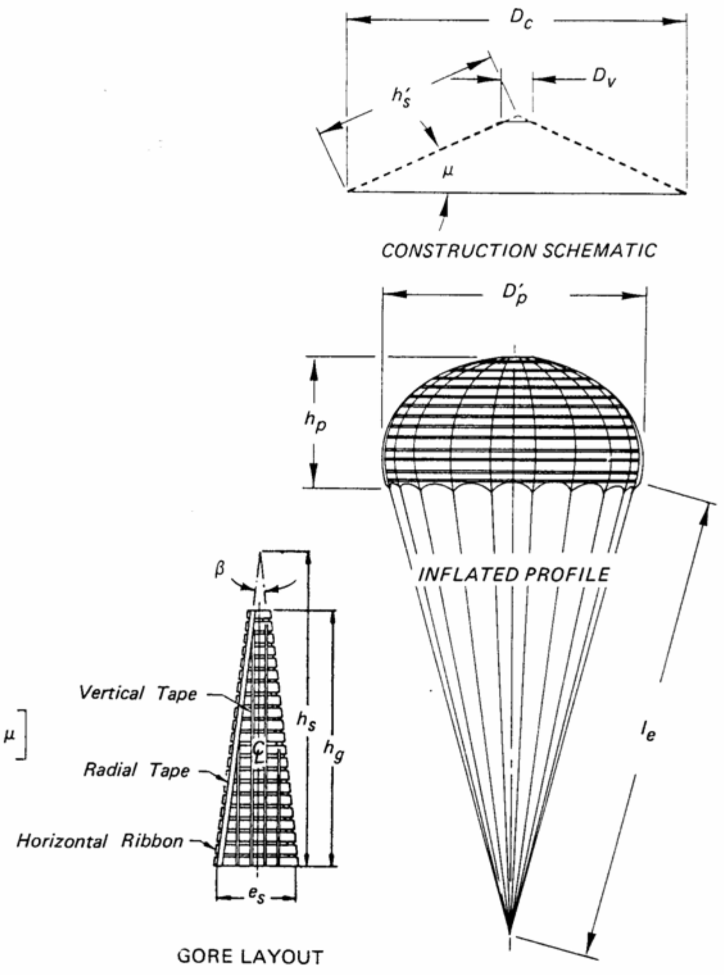
Flat ribbon parachute



Conical Ribbon Parachute



$$h_s = \left[\frac{S_o}{N \tan \beta/2}\right]^{1/2}$$

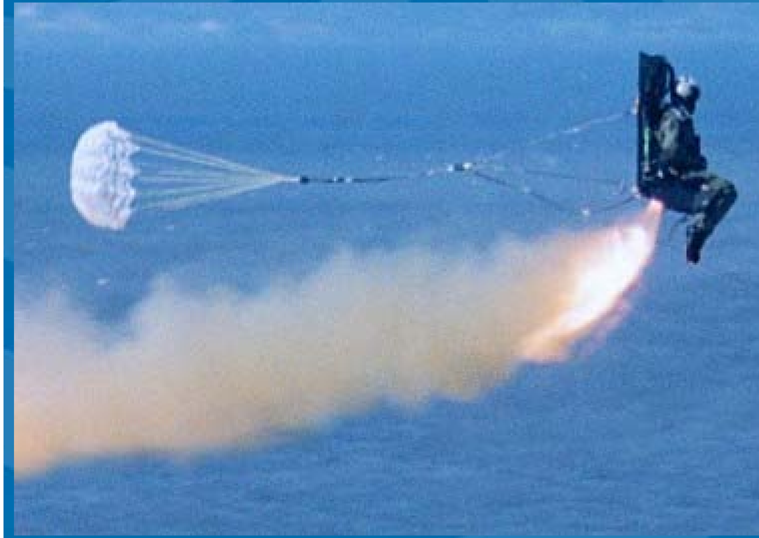
$$e_s = 2\, h_s \tan \beta/2$$

$$\beta = 2 \sin^{-1}\left[\left(\sin \frac{180^\circ}{N}\right) \cos \mu\right]$$

Generally:

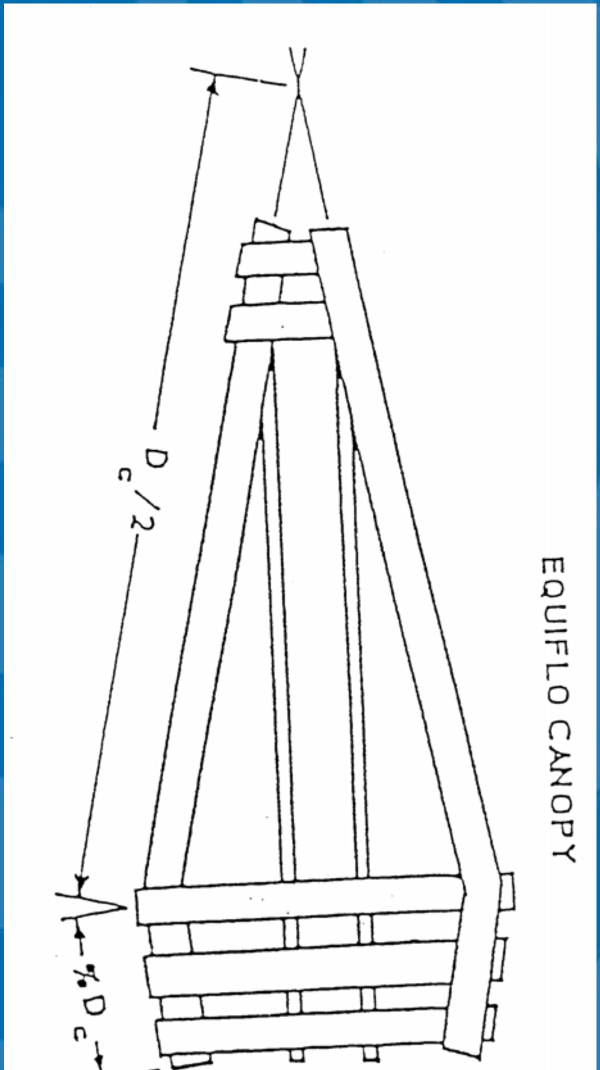
$$S_v < 0.01\ S_o$$

$$\frac{l_e}{D_o} = 1.00 \text{ to } 2.0$$



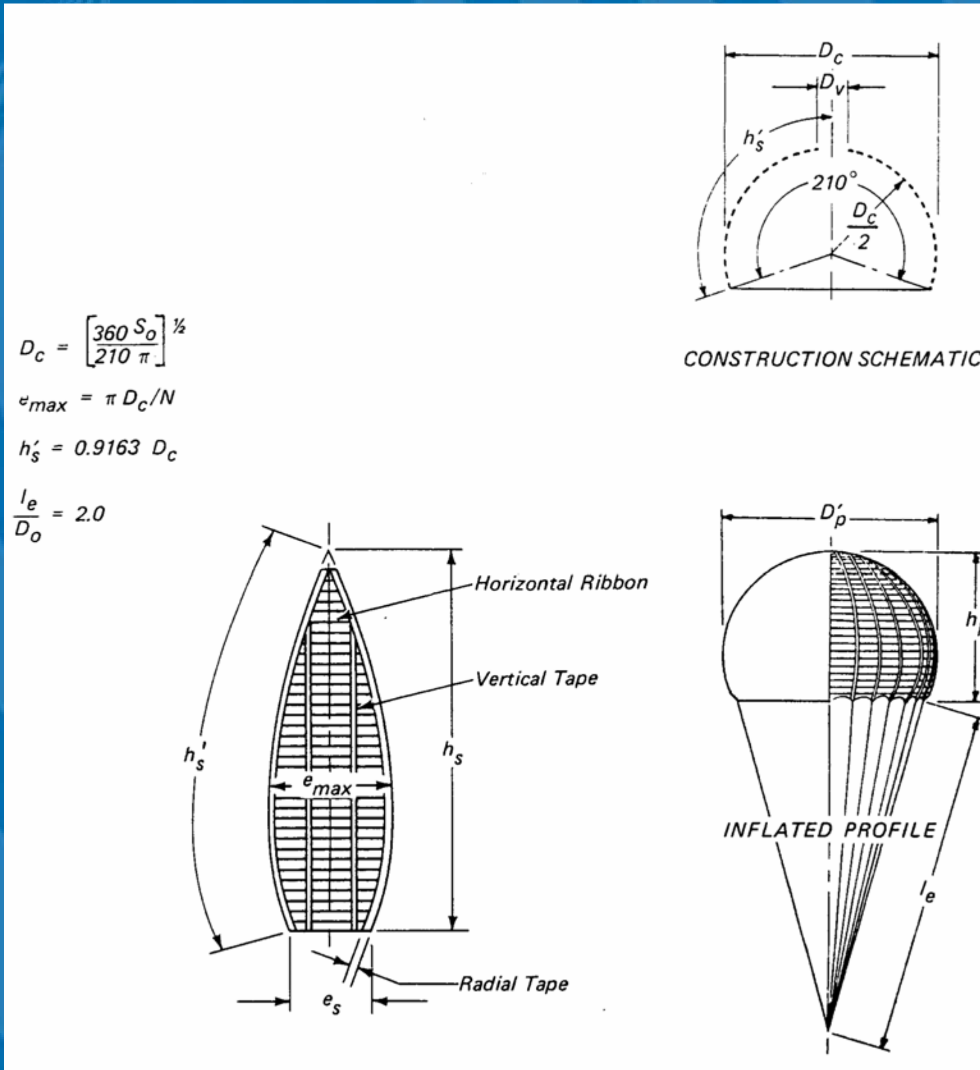
Equiflo Parachute

- Elimination of ribbon flutter
- 2 D_0 lines
- improved area ratio
- improved shape



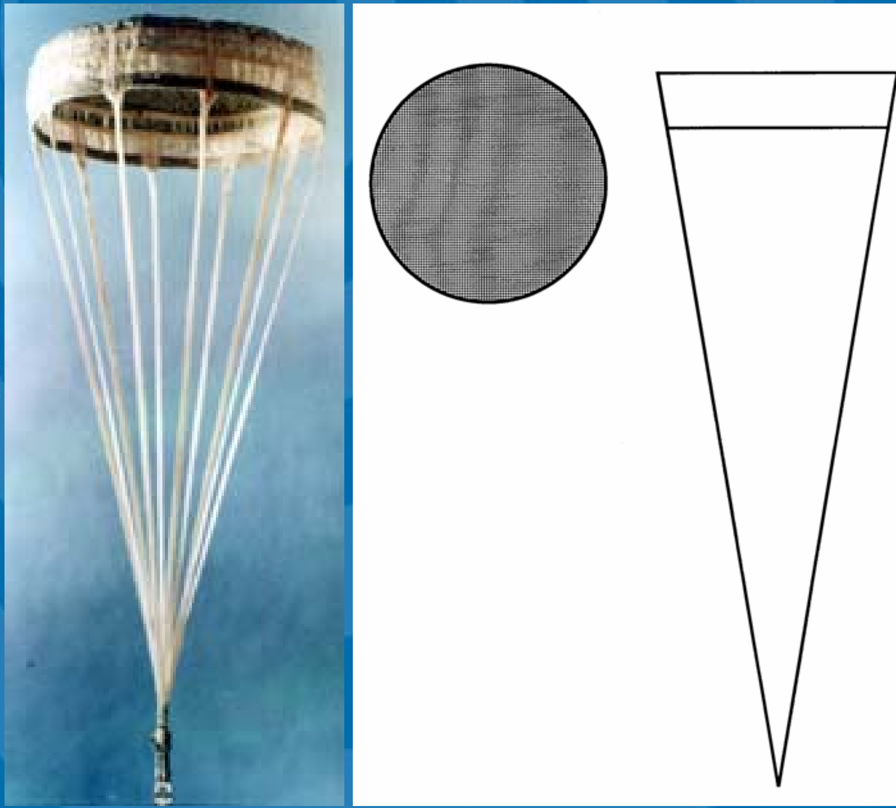
Hemisflo Parachute

- More refined shape
- effective to Mach 3



Hyperflo parachute

- Demonstrated at M 4.35 and Mach 6.0
- refined to parasonic hyperflo and tested at M 5.6



Supersonic-X parachute

- Tested from M1.75 to Mach 8.0

$D_{ex} = .3\ D_c$

$D_{in} = .8\ D_c$

$l_e = 2\ D_c$

$h_g = .9538\ D_c$

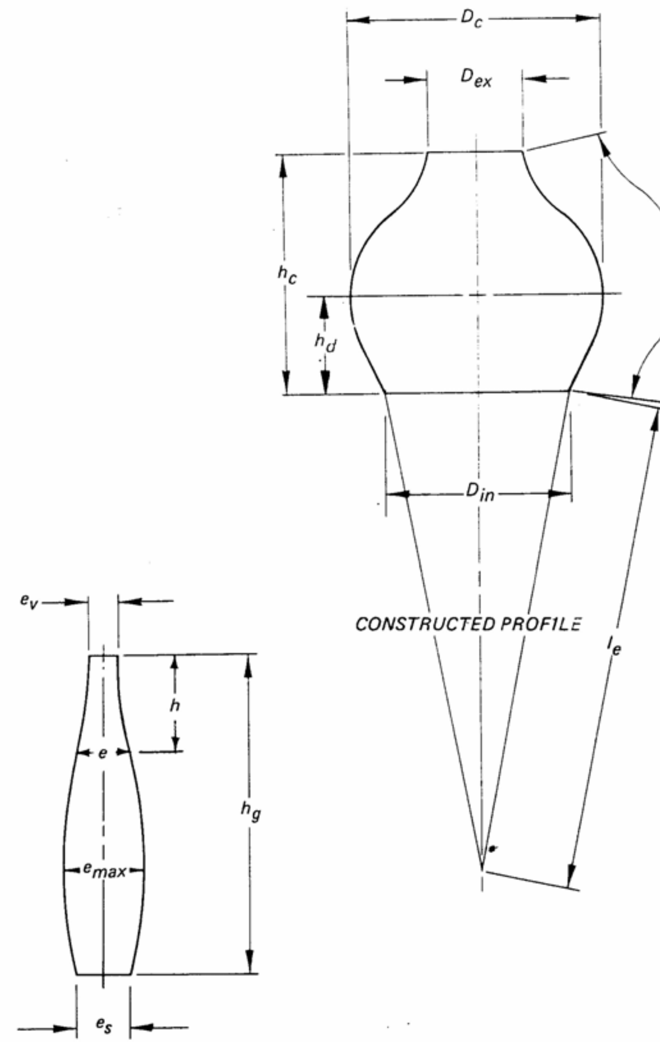
$e_{max} = \pi\ D_c/N$

$h_c = .775\ D_c$

$h_d = .3375\ D_c$

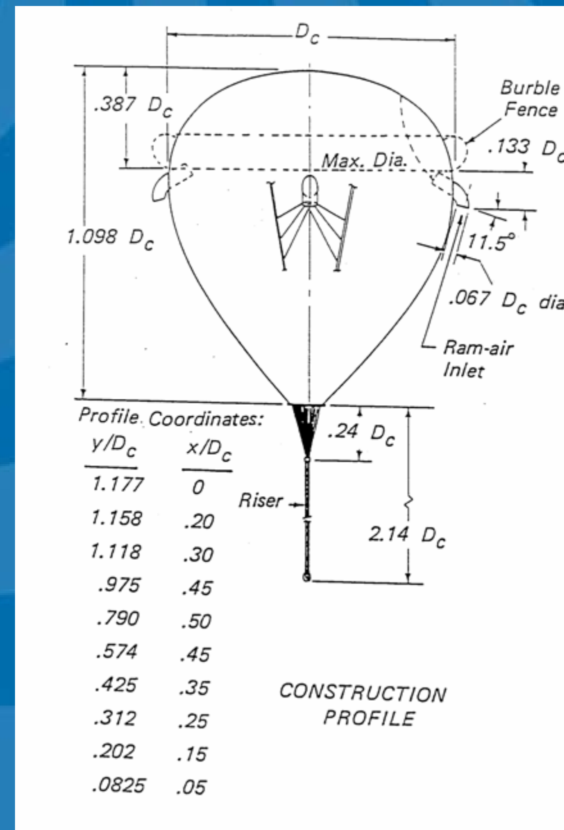
Gore Coordinates:

$\frac{h}{h_g}$	$\frac{e}{e_{max}}$
0	.230
.056	.317
.109	.367
.214	.527
.319	.703
.423	.856
.528	.955
.633	.997
.685	.997
.790	.947
.895	.875
1.00	.798



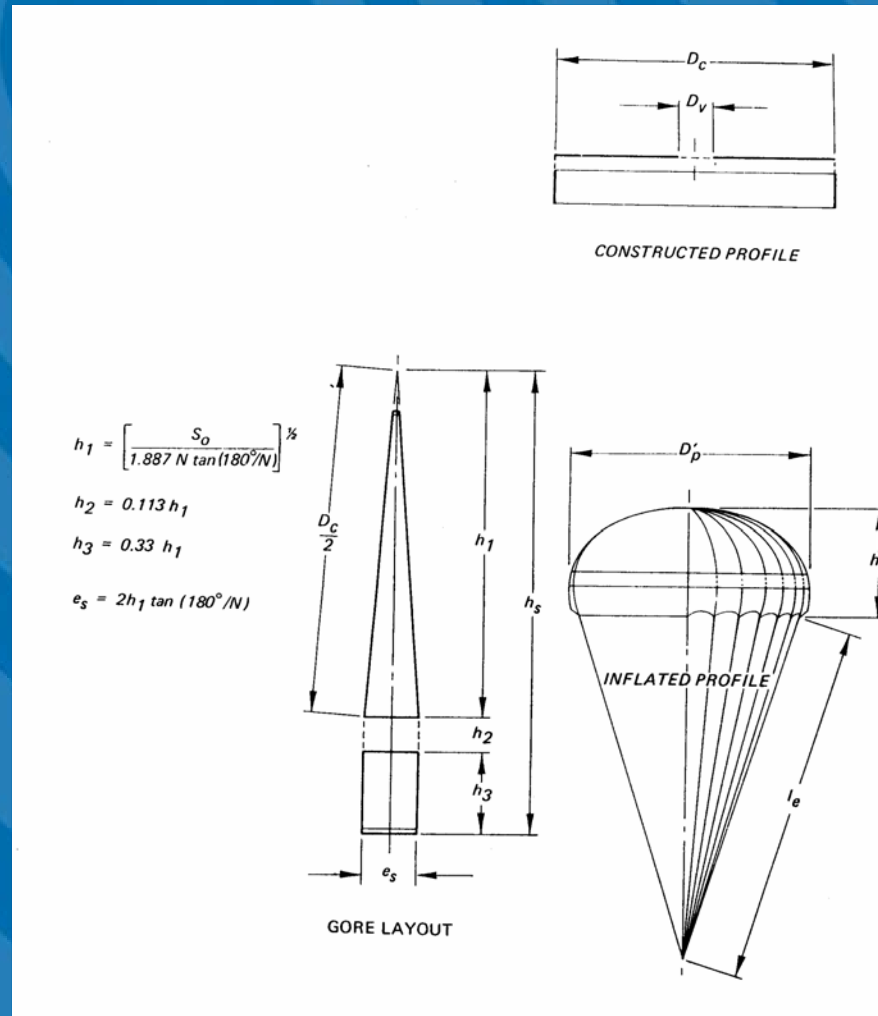
Ballute

- Internal or ram-air inflation
- 80° forward cone
- ellipsoidal rear
- burble fence
- tested to M 10.0



Disk-Gap-Band

- tested to M 2.72
- low q



Hermes testing

- Obtain comparative data for generic supersonic decelerators:
  - Cd
  - stability
- With known and documented
  - forebody geometry
  - mounting configuration / tunnel dimensions
  - wake
  - trailing distance
  - parachute detail designs

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Hermes Testing

- Test decelerators:
  - supersonic-X
  - conical ribbon
  - equiflo
  - hyperflo
  - ballute
- Critical dimensions
  - $D_p = 110$ mm
  - $L_l = 330$ mm
  - $D_P / D_B = 2.44$
  - $x_t / D_B = 8.4$

Huygens testing

- AEDC 16T tunnel
- 3/16 scale models
- aeroshell and ogive forebodies

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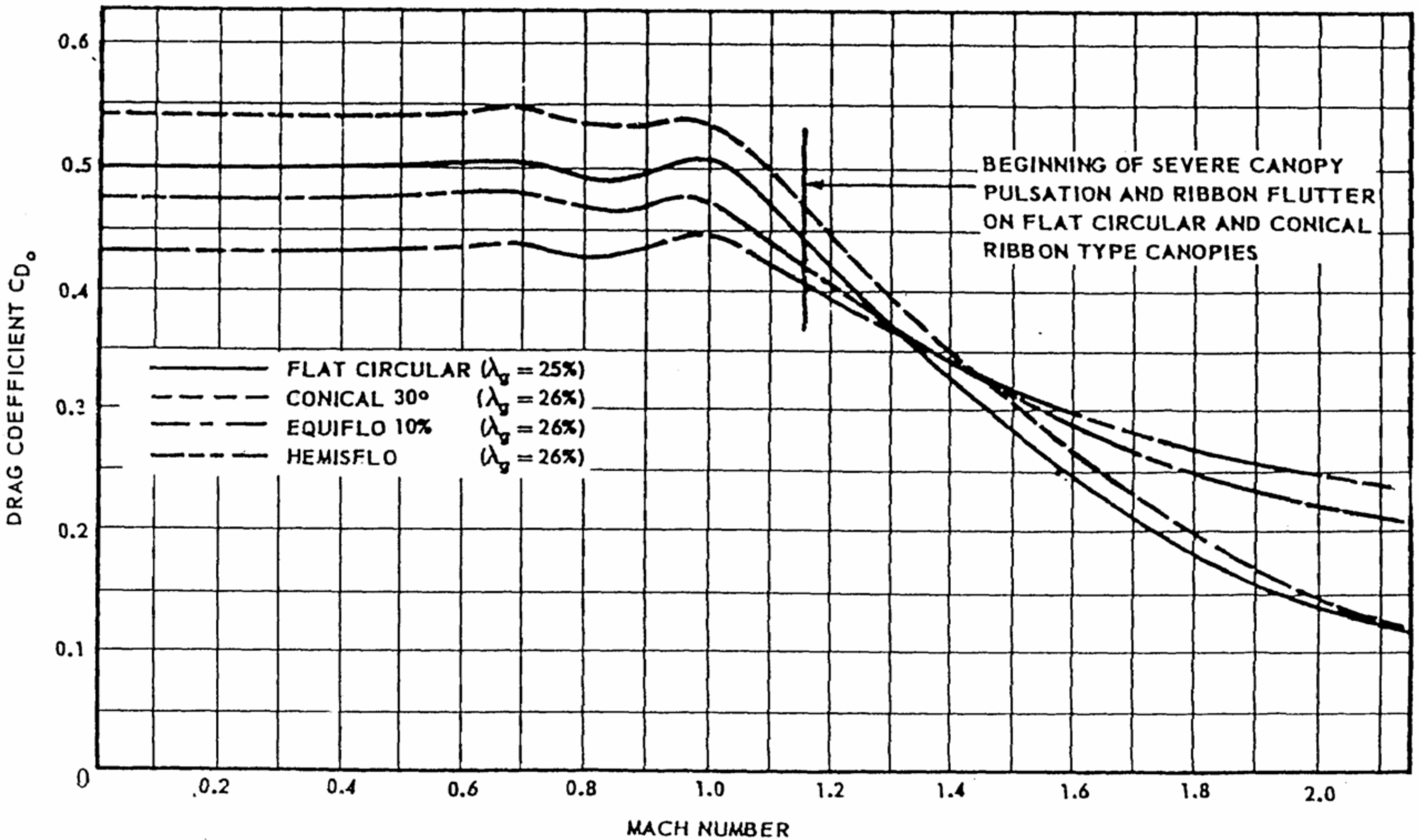
Ribbon parachute drag coefficient



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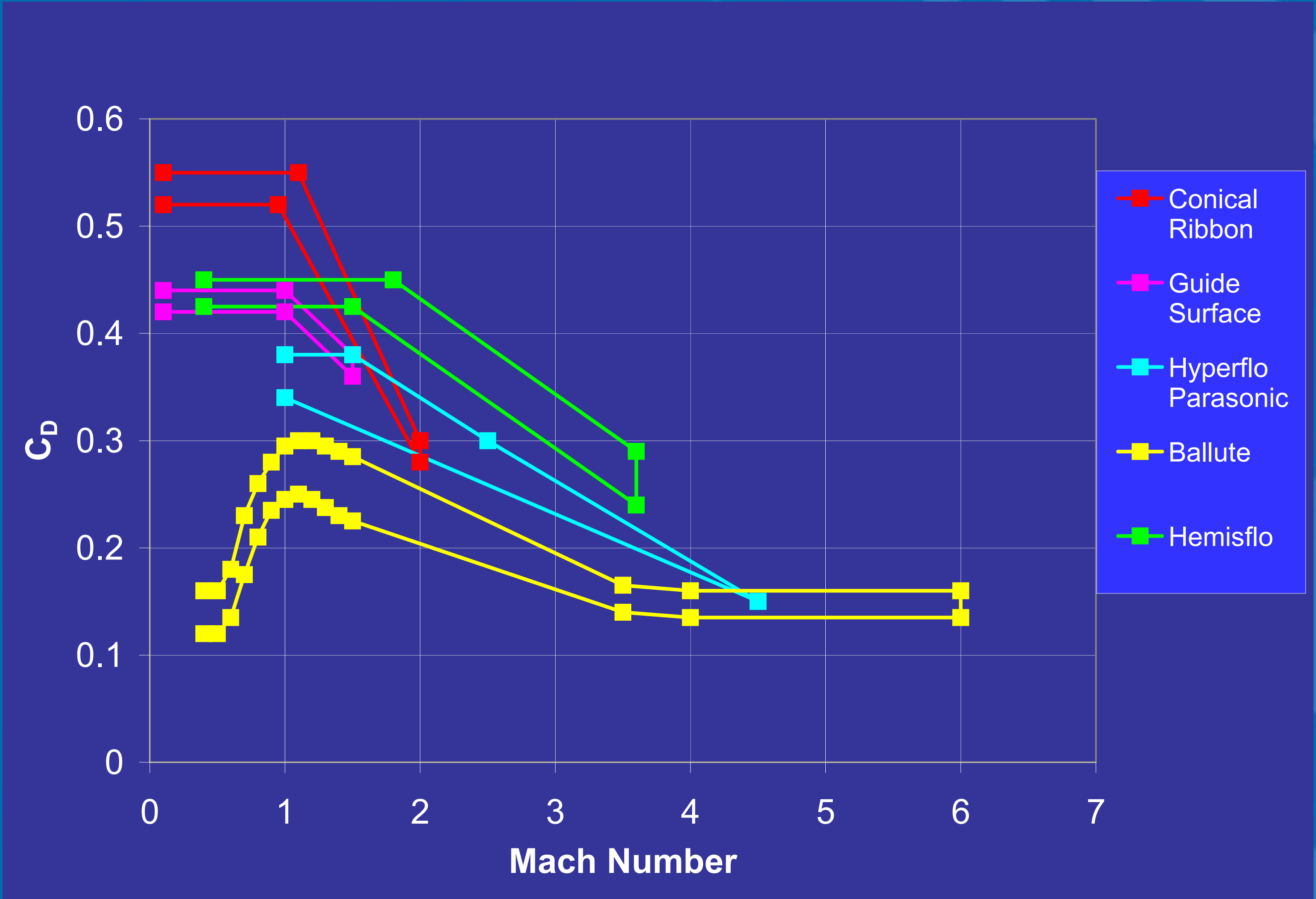
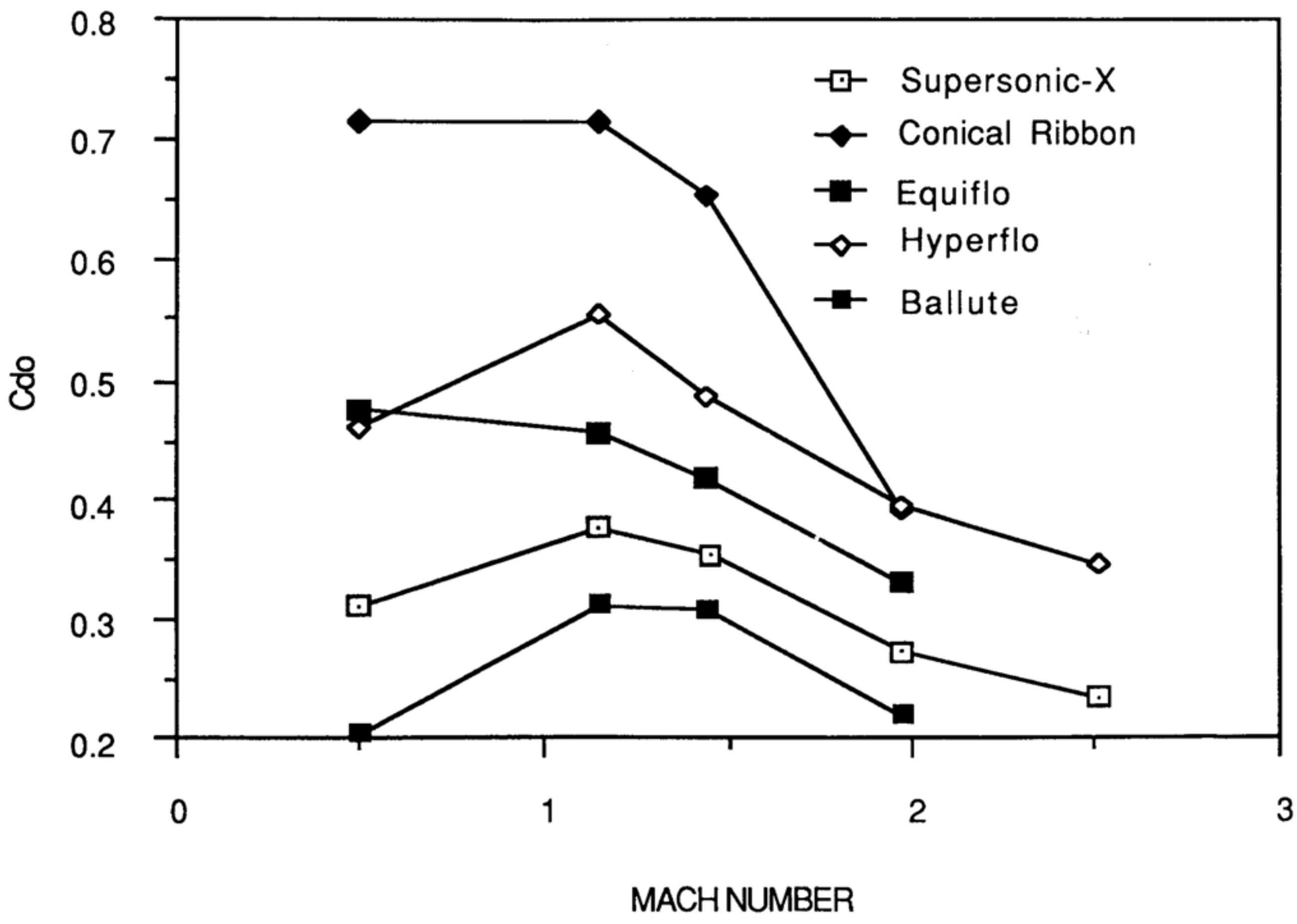
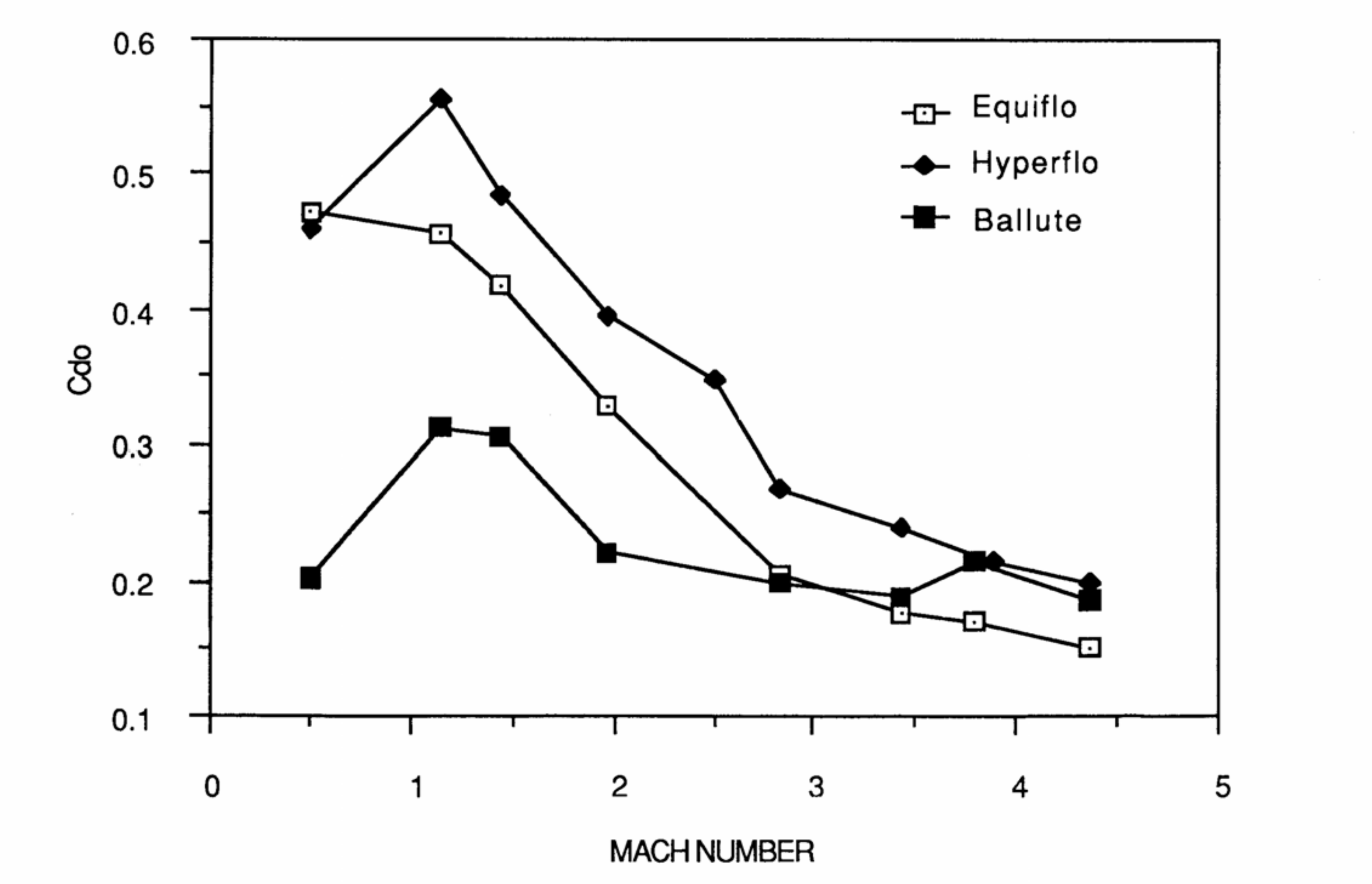
Drag coefficient versus Mach number



Drag coefficient vs M



Drag coefficient vs M



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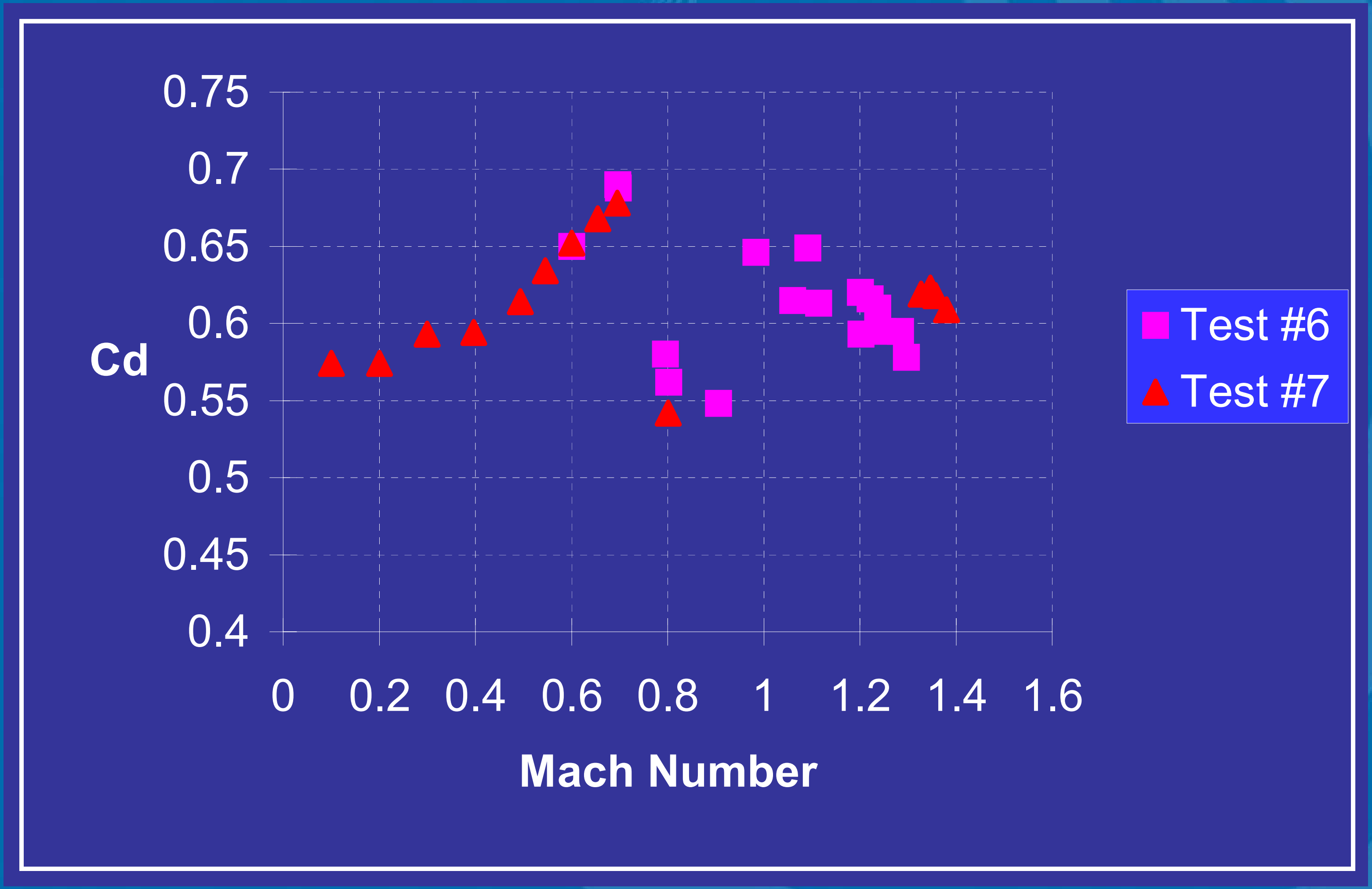
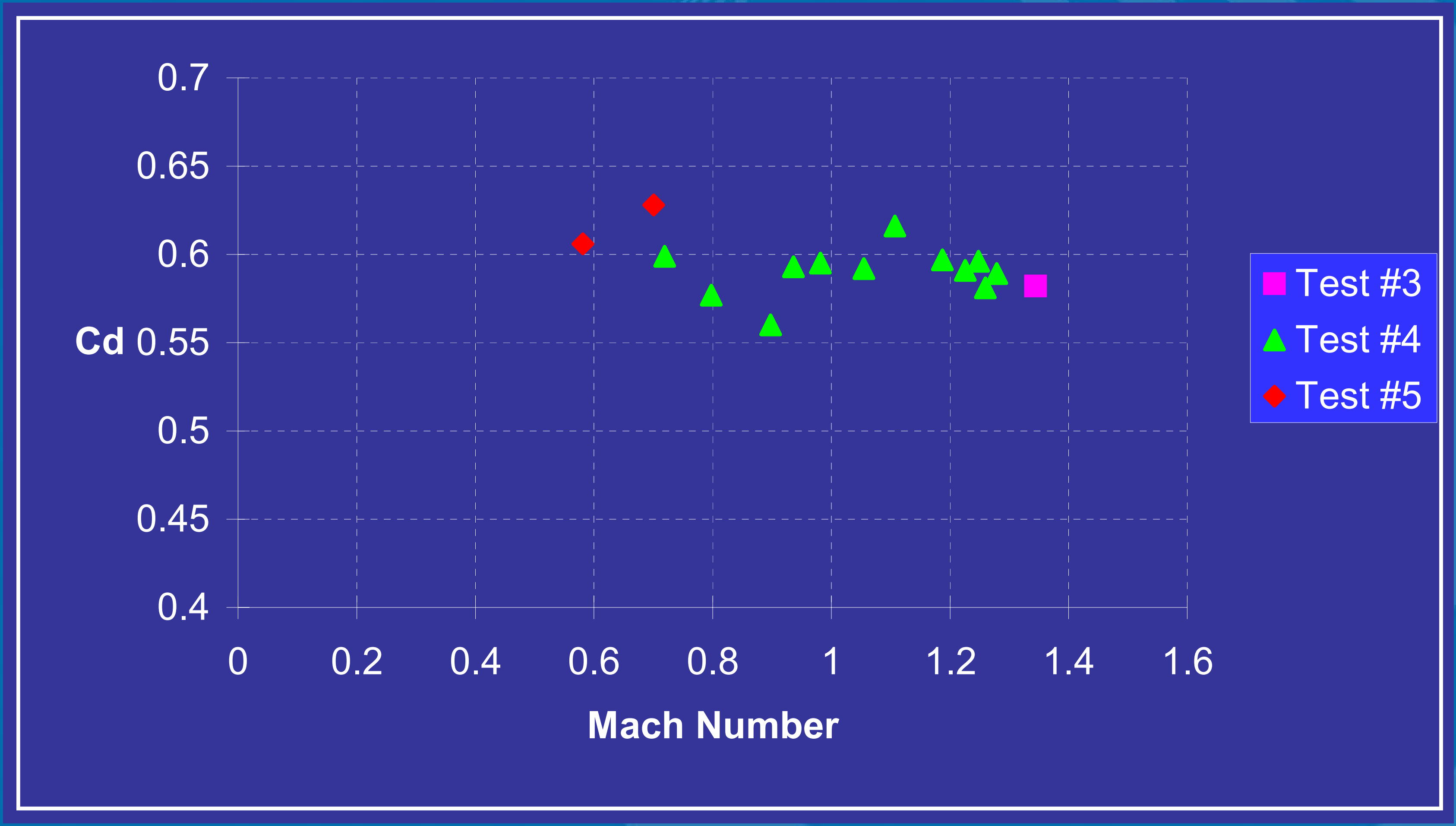
Huygens DGB main ogive wake



Huygens DGB main - probe wake



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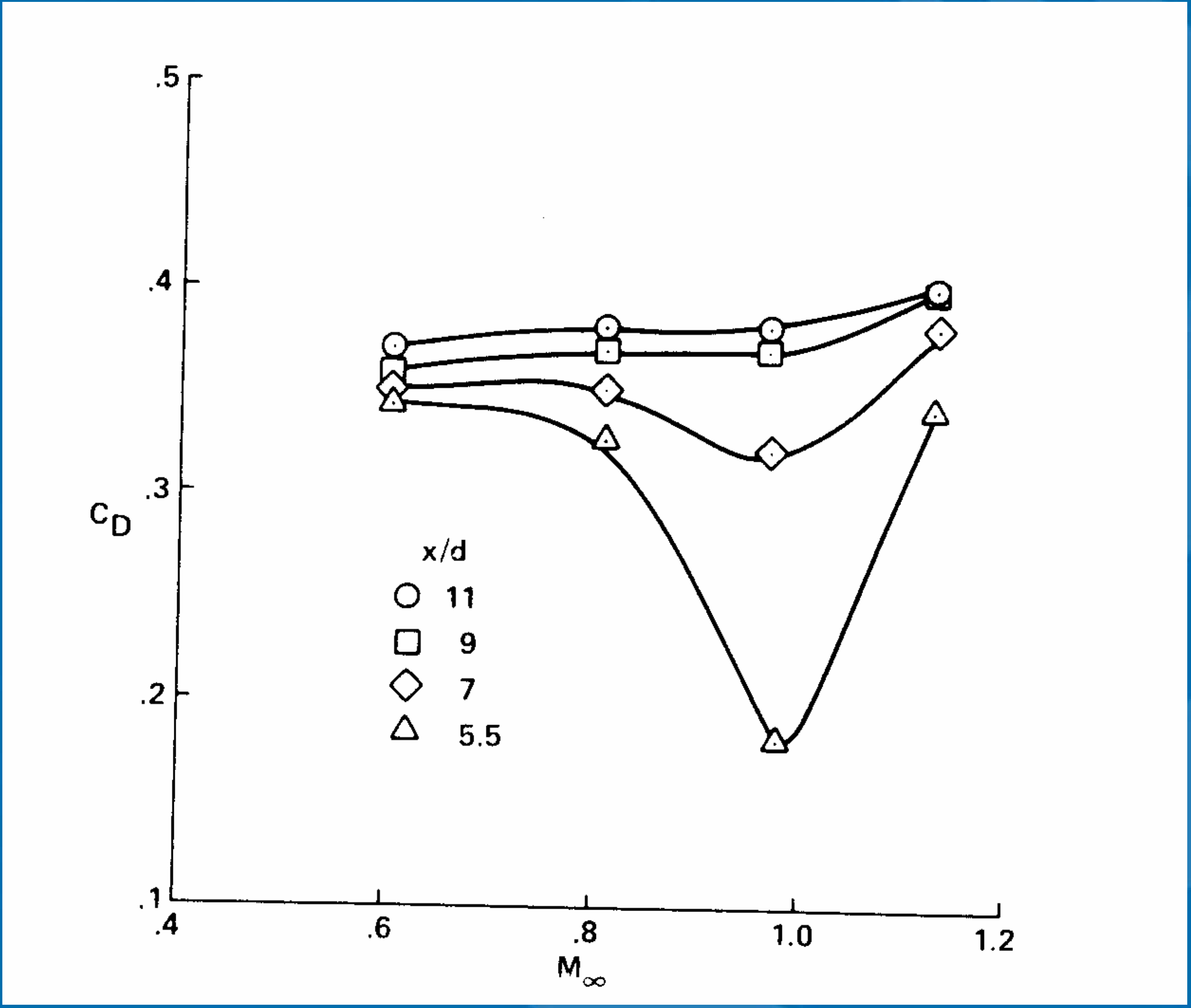
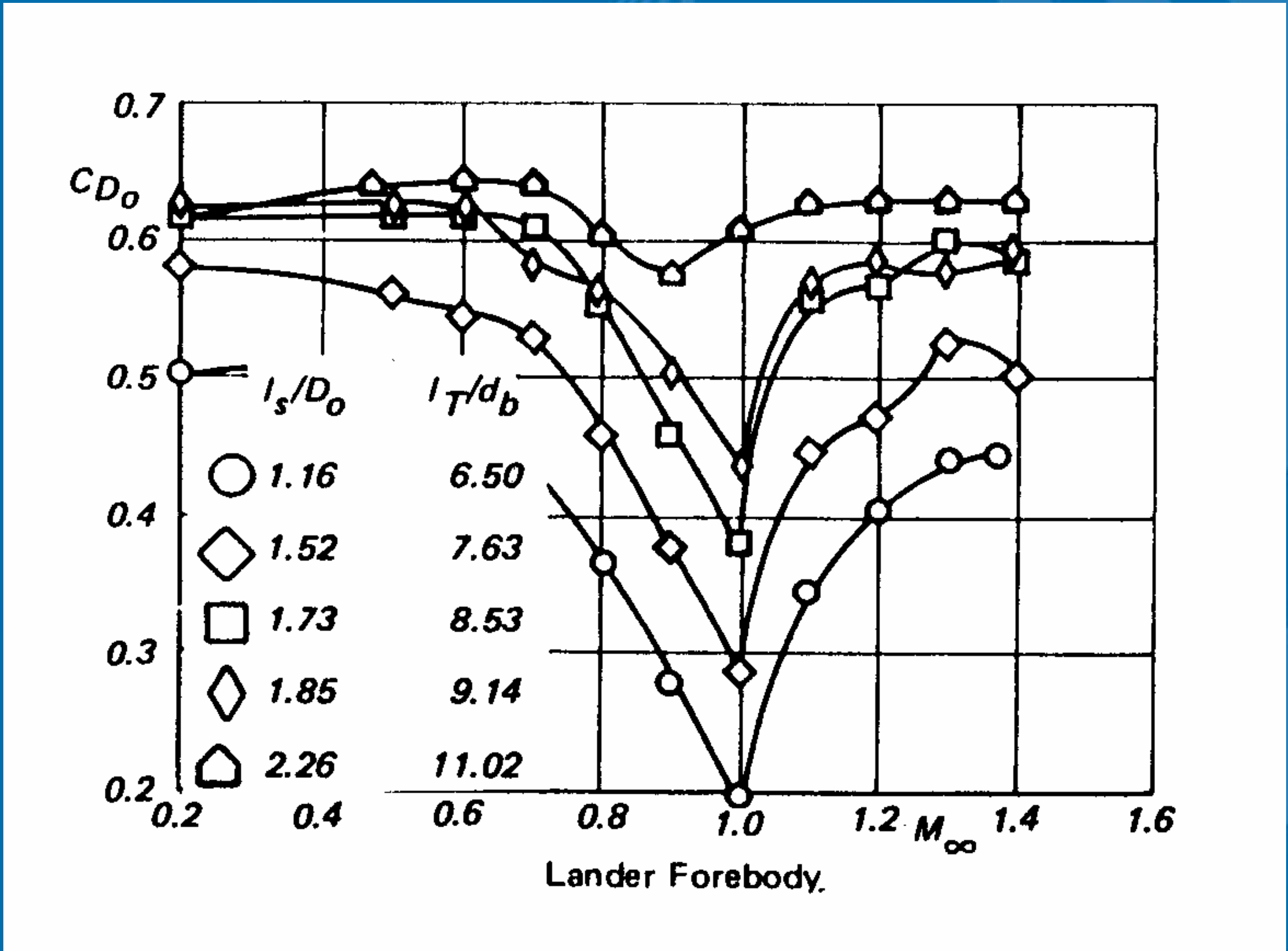
Galileo testing – transonic drag loss



Viking testing – transonic drag loss



Drag summary

- Conical ribbon - effective to M2.0
- Hemisflo - effective to M3.0
- Hyperflo - < M 4.0
- Ballute - good at all Mach numbers but low drag coefficient
- Supersonic-X
- DGB - good for low q up to M2.0

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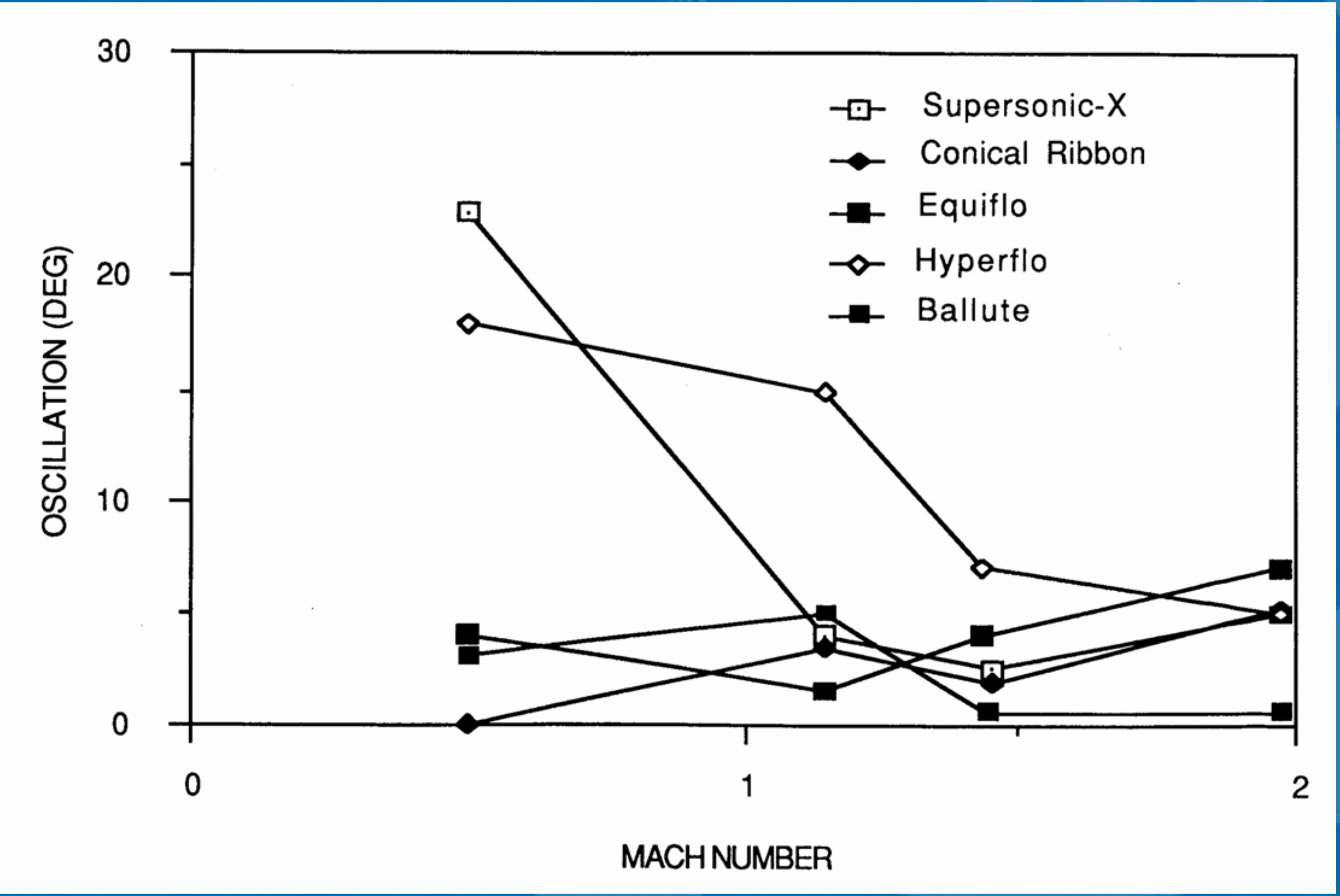
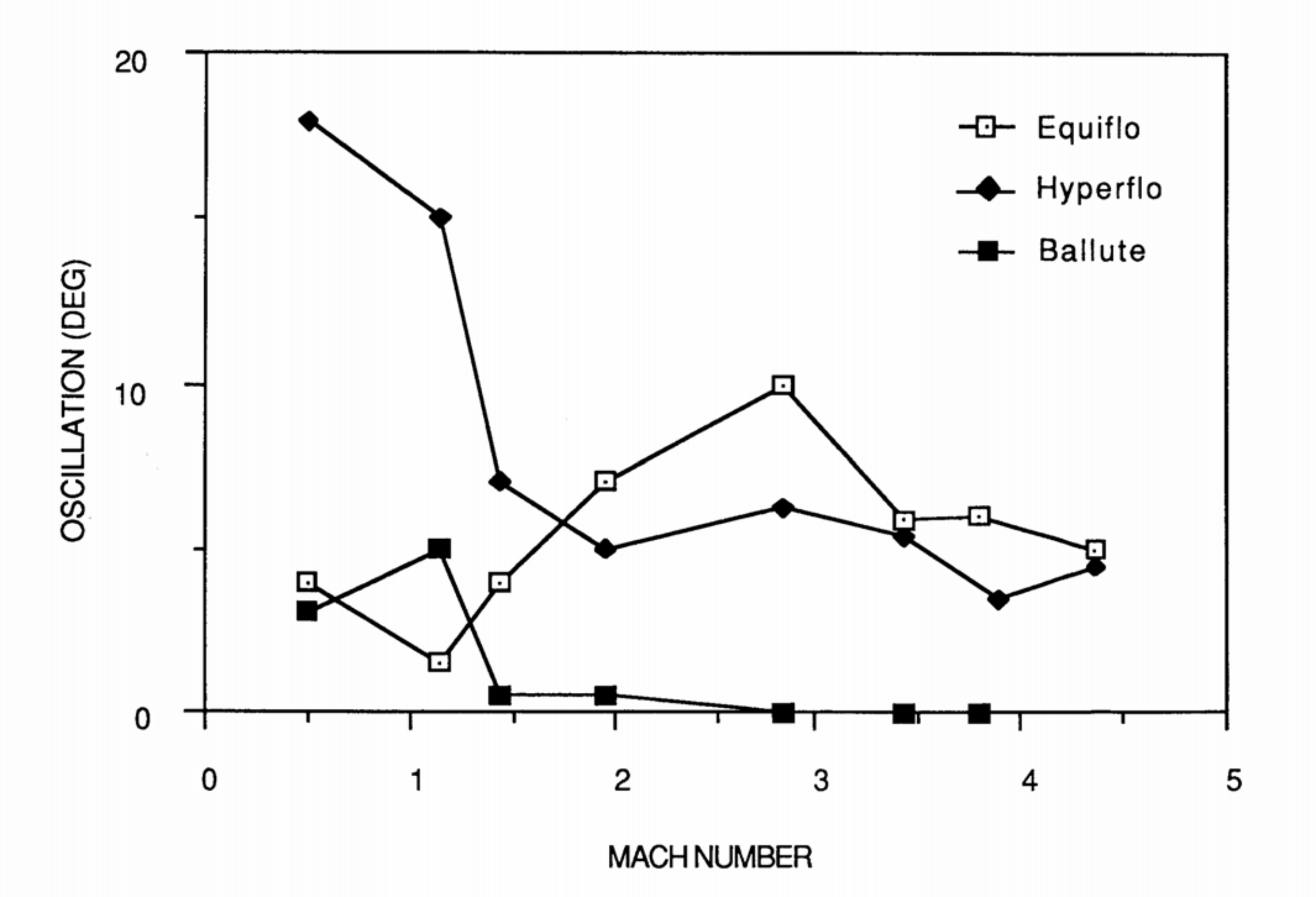
Stability vs M



Stability vs M



Supersonic Inflation

- subsonic flow: $K = v_s\, t_i \,/\, D_0$
- supersonic flow:
  - $K(\rho_C \,/\, \rho_0) = v_s\, t_i \,/\, D_0$ - Greene
  - $K(u_1 \,/\, u_2) = v_s\, t_i \,/\, D_0$
  - *these* are virtually equivalent since for continuity $u_1 \rho_1 = u_2 \rho_2$ across a shock wave

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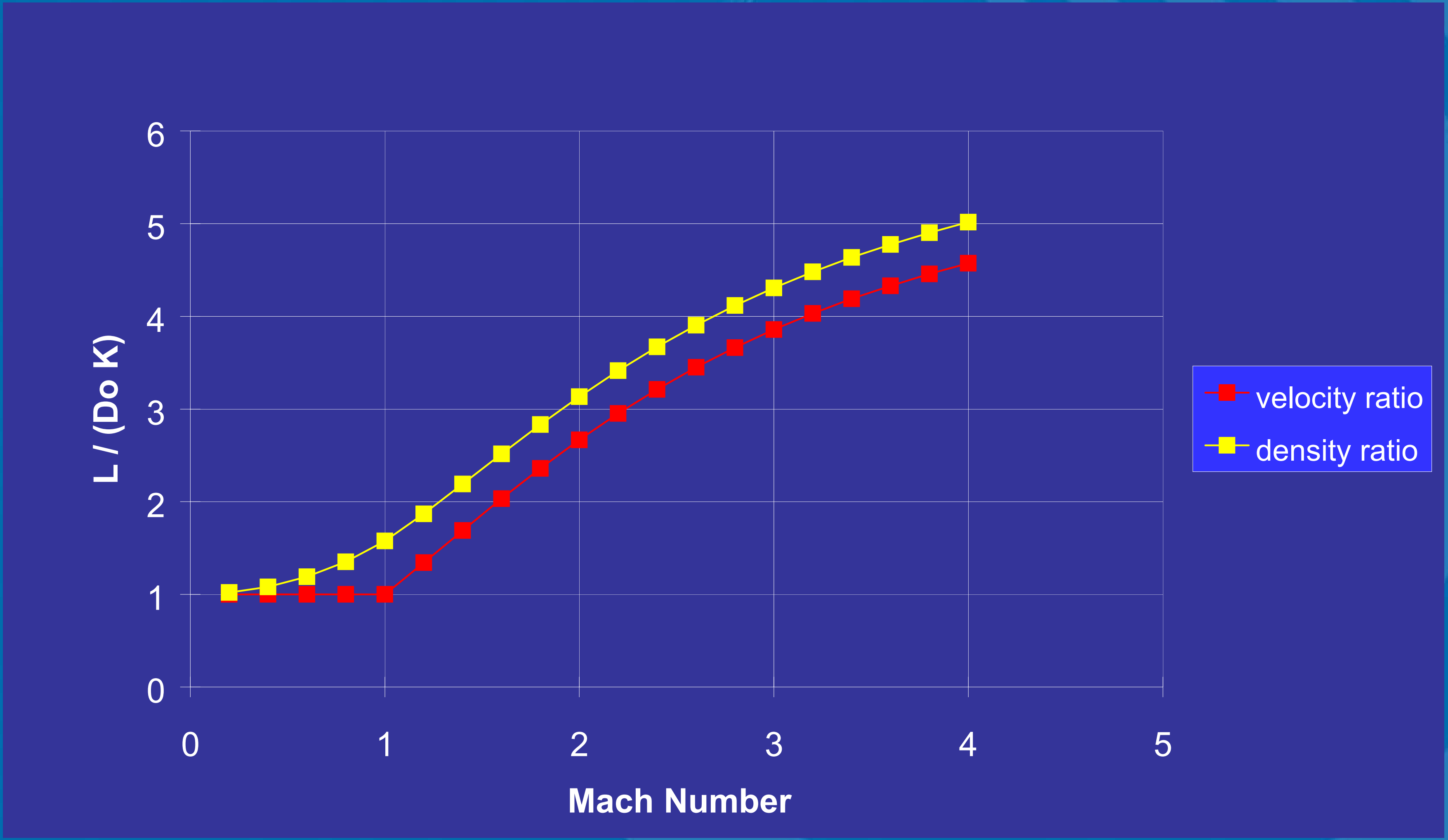
Inflation distance as function of Mach number



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Supersonic Inflation

- Use a code that explicitly includes added mass
- Experimentally derived dimensionless diameter evolution
- Use C_{d0} before wake interaction effects become apparent (subsonic)

Aerodynamic Heating

- stagnation temperature
  - $T_S = T_0 \left[1 + r\{ (\gamma - 1) / 2\} M^2 \right]$
- convection
  - $Q = h (T_S - T_W)$
- radiation
  - $Q = - \varepsilon \sigma T_W^4$

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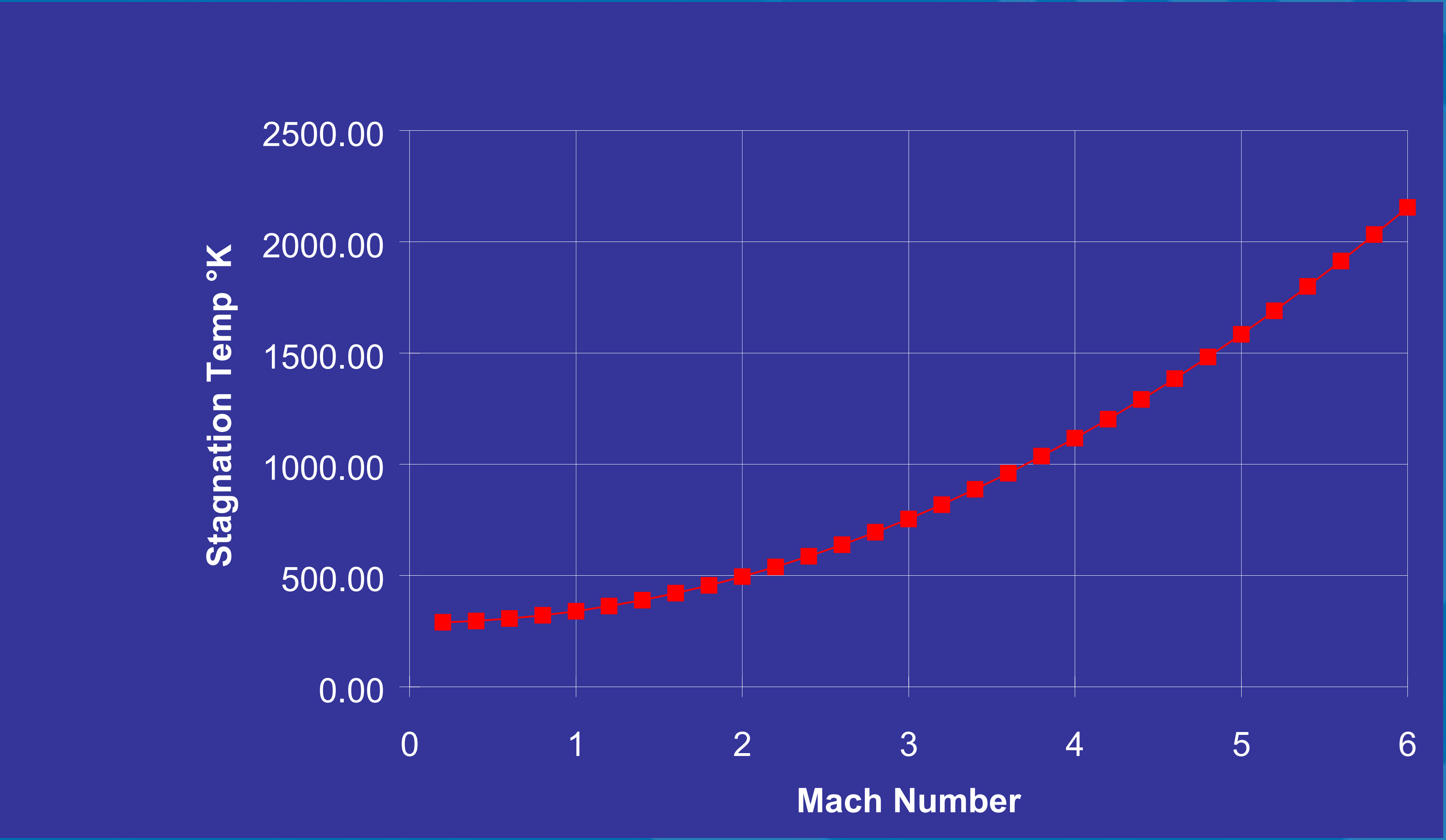
Aerodynamic heating



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Aerodynamic Heating

- high temperature materials
  - Nomex
  - Kevlar
  - steel wire
  - Ceramics
  - PBO
  - M5
- protective coatings
- internal cooling

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Design guide 1

- choose a parachute design that will be effective over the complete range of Mach numbers
- for low supersonic velocities (up to Mach 2) a conical ribbon parachute is usually the best option
- for operation at low dynamic pressure at up to Mach 2 + a disk-gap-band should be considered
- for velocities up to Mach 3 select a hemisflo
- above Mach 3 a hyperflo or supersonic-X may be applicable
- above Mach 4 it is generally better to use a ballute

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Design guide 2

- sometimes a multi-stage design is worth consideration using a specialist high Mach number device (such as the ballute) as the first stage with a parachute which has better low supersonic and sub-sonic performance (for example a conical ribbon parachute) as the second stage
- parachutes with shaped gores perform significantly better than conical or flat ribbon parachutes in supersonic flow
  - ribbon flutter is much reduced
  - the onset of pulsation is delayed
- ensure trailing distance is large 5 Dp is proposed

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Design guide 3

- longer suspension lines (at least $2D_0$) improve the performance of all parachute designs at supersonic speeds
  - drag performance with increasing Mach number is improved
  - inflation stability is markedly better
  - ribbon flutter is substantially reduced
  - the onset of pulsation delayed
- structural loads imposed during operation in supersonic flow are greater than those seen at equivalent dynamic pressures in subsonic flow
  - ribbon flutter and canopy shape changes
  - increased design margins are needed
  - careful detailed design, particularly in the skirt region, is important

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Design guide 4

- if aerodynamic heating is important use high temperature capable materials throughout the design and additionally consider coatings
- total heat pulse is important not the stagnation temperature
- deployment system - orderly deployment even more important at supersonic speeds than at subsonic velocities

- WHILST ALL ASPECTS OF SUPERSONIC AERODYNAMICS NOT PERFECTLY UNDERSTOOD
  WE CAN DESIGN SUCCESSFUL SYSTEMS

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- ANY QUESTIONS??

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